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Coincident Steam Generator Tube Rupture and Stuck-Open Safety Relief Valve Carryover Tests

COMPLETED
744

MB-2 Steam Generator Transient Response Test Program

Westinghouse Electric Corporation

Central Electricity Generating Board

Electric Power Research Institute

**Prepared for
U.S. Nuclear Regulatory
Commission**

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Coincident Steam Generator Tube Rupture and Stuck-Open Safety Relief Valve Carryover Tests

(MB-2 Steam Generator Transient Response Test Program)

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ABSTRACT

In PWR steam generator tube rupture (SGTR) faults, a direct pathway for the release of radioactive fission products can exist if there is a coincident stuck-open safety relief valve (SORV) or if the safety relief valve is cycled. In addition to the release of fission products from the bulk steam generator water by moisture carryover, there exists the possibility that some primary coolant may be released without having first mixed with the bulk water - a process called primary coolant bypassing. The MB-2 Phase II test program was designed specifically to identify the processes for droplet carryover during SGTR faults and to provide data of sufficient accuracy for use in developing physical models and computer codes to describe activity release.

The test program consisted of sixteen separate tests designed to cover a range of steady-state and transient fault conditions. These included a full SGTR/SORV transient simulation, two SGTR overfill tests, ten steady-state SGTR tests at water levels ranging from very low levels in the bundle up to those when the dryer was flooded, and three moisture carryover tests without SGTR. In these tests the influence of break location and the effect of bypassing the dryer were also studied. In a final test the behavior with respect to aerosol particles in a dry steam generator, appropriate to a severe accident fault, was investigated.

The main conclusions from these tests were that moisture carryover was very low in the absence of an SGTR, that there was no significant increase in moisture carryover during an SGTR/SORV fault and that very little or no primary coolant passed through the steam generator without having first completely mixed with the bulk secondary liquid (primary coolant bypassing). Short-term perturbations to steady-state conditions were found to produce transient releases, which could be mainly due to primary coolant bypassing or carryover, depending on type of transient and on water level. While small, these releases were the equivalent of steady-state releases over tens of hours, and could be important factors in determining the overall activity release in these types of fault. At very low water levels, when recirculation within the boiler could not be maintained, conditions typical of early stages

ABSTRACT (Continued)

in an SGTR/SORV fault produced large transient releases. These are believed to be due to the rewetting of dry deposits formed on the exposed tube bundle. Similar releases were not produced under conditions typical of later stages in an SGTR/SORV fault.

Based on the MB-2 data it is suggested that the steady-state MB-2 value of 0.001% should be used to assess primary coolant bypassing in SGTR/SORV faults. Under these fault conditions it is suggested that moisture carryover should be taken as 0.005%. This carryover value represents a factor of ten increase over that found in the present tests and, apart from a question of prudence, is chiefly determined by a comparison between the results from the MB-2 tests and plant at 100% load. A verification of this factor of safety could only be made from a detailed assessment of the known, but largely unquantified, influence of minor differences in design and disposition of the separators and dryers as well as the scaling factors associated with changing from a segment of a steam generator, as in MB-2, to a complete unit.

The test data show that short-term perturbations to steady-state or near steady-state conditions can result in transient releases that may account for a substantial part of the total release. The types of perturbation tested in MB-2 may not all necessarily occur in plant, but the most significant perturbation, opening the safety relief valve, is expected to occur in many SGTR fault sequences. If the MB-2 data are applied to a typical SGTR sequence, it is predicted that the quantity of primary coolant released by primary coolant bypassing will be dominated by the transient release on opening the safety relief valve.

Comparing the present test data with the current calculational procedure for radiological releases shows that the MB-2 test data predict a release by primary coolant bypassing that is two orders of magnitude less than that predicted by the current procedure. As this will have a significant impact on the total activity release, it is suggested that the implication of these findings to plant should be considered when the current calculational procedure is next revised.

CONTENTS

Section Page

1 INTRODUCTION 1-1

1-1. Test Matrix 1-2
1-2. Testing Methodology 1-5
1-3. References 1-6

2 THE MB-2 TEST FACILITY 2-1 -11

2-1. Description of Model Boiler . 2-1
2-1-1. Tube Bundle 2-2 -12
2-1-2. MB-2 Upper Shell Region 2-3 -13
Modular Primary Separator 2-7 -17
Downcomer 2-7
Feedwater Inlet 2-7
Structural Protection 2-7
2-2. Test Loop Description 2-9 -19
2-2-1. General Description 2-9
2-2-2. Primary Loop 2-9
Primary Loop Makeup System 2-9
Steam Generator Tube Rupture (SGTR) System 2-10-20
2-2-3. Secondary Loop 2-11-21
Stuck-Open Relief Valve (SORV) Lines 2-11
Feedwater System 2-12-22
2-2-4. Tertiary Loop 2-14-24
2-2-5. Chemical Sampling System 2-14
Primary Sample Point 2-15-25
Model Boiler Sample Points 2-15
SORV Condensate Sample Point 2-16-26
2-3. References 2-19-29

3 TEST FACILITY INSTRUMENTATION 3-1 -47

3-1. Tube Bundle 3-1
3-1-1. Thermocouples 3-1
3-1-2. Pressure Taps and Differential Pressure Measurements 3-3-49
3-2. Lower Downcomer 3-5-51
3-2-1. Pressure Taps and Differential Pressure Measurements 3-5
3-2-2. Thermocouples 3-7-53
3-3. Upper Shell Region 3-9-55
3-3-1. Pressure Taps and Differential Pressure Measurements 3-9
3-3-2. Thermocouples 3-10-56
3-4. Loop Instrumentation 3-12-58
3-5. Data Aquisition System Description 3-14 -60
3-6. References 3-15 -61

CONTENTS (Cont)

Section Page

4 CHEMICAL CONTROL AND INSTRUMENTATION 4-1 -73

4-1. Analytical Measurements 4-1
  4-1-1. Continuous Monitors 4-1
  4-1-2. Batch Analyses 4-2 -74
4-2. Chemistry Control During Transient Tests 4-3 -75
  4-2-1. Loop Chemistries 4-4 -76
  4-2-2. Sampling and Monitoring 4-5 -77

5 TEST PERFORMANCE 5-1 -80

Test 1 - 2% SORV Flow with SGTR at Bottom of Tube Bundle (T-1952) 5-1

Test 2 - 8% SORV Flow with SGTR at Top of Tube Bundle and Low S/G Water Level (T-1958) 5-4 -83

Test 3 - 8% SORV Flow with SGTR at Bottom of Tube Bundle (T-1970) 5-8 -87

Test 4 - 10% SORV Flow with SGTR at Bottom of Tube Bundle (T-1982) 5-10 -89

Test 5 - 8% SORV Flow with SGTR at Bottom of Tube Bundle (T-1972) 5-13 -92

Test 6 - 8% SORV Flow Moisture Carryover Test (T-1957) 5-15 -94

Test 7 - 100% Power Moisture Carryover Test (T-1966) 5-17 -96

Test 8 - 10% SORV Flow, Blowdown from 442 in. to 54 in. and Operation with SGTR at Top of Tube Bundle at Four Water Levels (T-1975 - T-1979) 5-21 -100

Test 9 - 10% SORV Flow, Blowdown from 442 in. to 54 in. and Operation with SGTR at Bottom of Tube Bundle at Four Water Levels (T-1988 - T-1992) 5-27 -106

Test 10 - Overfill Transient with SGTR at Top of Bundle, 10% SORV Flow (T-1998) 5-33 -112

Test 11 - Overfill Transient with SGTR at Top of Bundle, 10% SORV Flow (T-2003) 5-36 -115

Test 12 - Transient Test with SGTR at Top of Bundle, 2% - 10% SORV Flow (T-2001) 5-39 -118

Test 13 - 100% Power Moisture Carryover Test with Dryer Bypassed (T-2069) 5-44 -123

CONTENTS (Cont)

Section Page

Test 14 - 10% SORV Flow with SGTR at Bottom of Tube Bundle and with Dryer Bypassed (T-2067) 5-46 -125

Test 15 - 10% SORV Flow, Blowdown from 442 in. to 48 in. and Operation with SGTR at Top of Tube Bundle at Four Water Levels with the Dryer Bypassed (T-2050 - T-2054) 5-50 -129

Test 16 - 10% SORV Flow, Blowdown from 442 in. to 57 in. and Operation with SGTR at Bottom of Tube Bundle at Four Water Levels with Dryer Bypassed (T-2061 - T-2065) 5-56 -135

6 MASS DISTRIBUTION IN MB-2 6-1 -502

7 EVALUATION OF RESULTS 7-1 -513

7-1. Analytical Results 7-1
Low Concentration Samples 7-2 -514
High Concentration Samples 7-5 -517
7-2. Assessment of Model Boiler Concentrations 7-6 -518
7-3. Carryover and Bypassing 7-11 -523
Steady-State Definitions 7-11
Transient Release Definitions 7-13 -525
7-3-1. Carryover and Bypassing at Normal or High Water Level 7-14 -526
7-3-2. Carryover and Bypassing at Low Water Level 7-18 -530
Blowdown and Boildown 7-18
SGTRs and Other Events at Very Low Water Levels 7-21 -533
SGTRs and Other Events at Intermediate Water Levels 7-25 -537
7-4. Assessment of Test Results 7-27 -539
7-5. References 7-32 -544

8 DISCUSSION AND CONCLUSIONS 8-1 -564

8-1. Carryover and Bypassing 8-1
Sources of Fine Drops for Carryover 8-4 -567
Injection of SGTR Break Water 8-9 -572
Flow Conditions at Very Low Water Level 8-10 -573
Transient Releases When Circulation Collapses 8-14 -577
Transient Releases 8-16 -579
8-2. Application to Full-Scale Steam Generators 8-18 -581
Steam Generator Under Recirculating Conditions 8-18
Steam Generator at Very Low Water Levels 8-23 -586
Comparison with Radiological Release Calculations for SGTR Faults 8-23
8-3. Conclusions 8-27 -590
8-4. References 8-32 -595

CONTENTS (Cont)

Section		Page
Appendix A	Test Report: MB-2 Aerosol Attenuation Test	A-1 -598
Appendix B	MB-2 Data Channel/Instrumentation List	B-1 -624
Appendix C	Data Tapes	C-1 -630
Appendix D	MB-2 Thermal-Hydraulic Data Reduction	D-1 -632

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LIST OF FIGURES

Figure		Page
2-1	Model Boiler No. 2 Configuration During Phase II Tests ..	2-20
2-2	Westinghouse Model F Steam Generator	2-21
2-3	MB-2 Bundle Cross-Section	2-22
2-4	MB-2 U-Tube Dimensions	2-23
2-5	MB-2 Upper Shell Region	2-24
2-6	MB-2 Cross-Section at Deck Plate	2-25
2-7	Flow Paths in MB-2 Upper Shell Region	2-26
2-8	Modular Separators Configured in a Model F Shell	2-27
2-9	MB-2 Internal Check Valves	2-28
2-10	Primary Loop Schematic	2-29
2-11a	Loop Modifications for SGTR Tests	2-30
2-11b	Routing of Lower SGTR Break Element Tubing	2-31
2-11c	SGTR Break Element at 282.0 in. Elevation	2-32
2-11d	Schematic of Tertiary Loop	2-33
2-12	Schematic of Feedwater System	2-34
2-13	Isometric Sketch of SORV Piping and Condenser	2-35
2-14	Schematic of Chemical Sampling System	2-36
3-1	Location of MB-2 Tube Bundle Thermocouples	3-16
3-2	MB-2 Bundle Cross-Section and Super Cell Locations	3-17
3-3	MB-2 Primary Thermocouple Configurations	3-18
3-4	MB-2 Secondary Thermocouple Configurations	3-19
3-5	MB-2 Tube Wall Thermocouple Configurations	3-20

LIST OF FIGURES (Continued)

Figure Page

3-6 MB-2 Thermocouple Dimensions 3-21

3-7 Secondary Side Pressure Taps Within Tube Bundle 3-22

3-8 Pressure Taps and Thermocouples Within MB-2 Downcomer Pipes 3-23

3-9 Location of Dead Space and Wrapper Box Wall Thermocouples 3-24

3-10 Location of Pressure Taps and Thermocouples in MB-2 Upper Shell Region (Phase II Tests) 3-25

3-11 MB-2 Primary and Secondary Loop Instrumentation 3-26

5-1 Primary System (Pressurizer) Pressure (P-139): Test No. 1 (T-1952) 5-103

5-2 Primary Fluid T_{hot} (T-1150): Test No. 1 (T-1952) 5-103

5-3 Primary Fluid Flow Rate (WF-109): Test No. 1 (T-1952) .. 5-104

5-4 Secondary Side Pressure (P-7): Test No. 1 (T-1952) 5-104

5-5 Downcomer Water Level - Narrow Range (WL-9368): Test No. 1 (T-1952) 5-105

5-6 SGTR Flow Rate (WF-150): Test No. 1 (T-1952) 5-105

5-7 SORV Flow Rate (WF-01): Test No. 1 (T-1952) 5-106

5-8 SORV Tank Level (LT-3): Test No. 1 (T-1952) 5-106

5-9 Hot Leg Downcomer Flow Rate (WDCHL): Test No. 1 (T-1952) 5-107

5-10 Cold Leg Downcomer Flow Rate (WDCCL): Test No. 1 (T-1952) 5-107

5-11 Secondary Fluid Temperature (STC-7): Test No. 1 (T-1952) 5-108

5-12 Secondary Fluid Temperature (STC-41): Test No. 1 (T-1952) 5-108

5-13 Secondary Fluid Temperature (STC-53): Test No. 1 (T-1952) 5-109

LIST OF FIGURES (Continued)

Figure | Page

5-14 Integrated SGTR Flow: Test No. 1 (T-1952) 5-109

5-15 Variation in Tracer Concentrations: Test No. 1 (T-1952) 5-110

5-16 Comparison Between S-1 (○) and IKP-4 (▲) Results After Correcting for Sample Line Delays: Test No. 1 (T-1952) . 5-111

5-17 Primary System (Pressurizer) Pressure (P-139): Test No. 2 (T-1958) 5-112

5-18 Primary Fluid T_{hot} (T-1150): Test No. 1 (T-1958) 5-112

5-19 Primary Fluid Flow Rate (WF-109): Test No. 2 (T-1958) .. 5-113

5-20 Secondary Side Pressure (P-7): Test No. 2 (T-1958) 5-113

5-21 Downcomer Water Level - Wide Range (WL-9321): Test No. 2 (T-1958) 5-114

5-22 SGTR Flow Rate (WF-150): Test No. 2 (T-1958) 5-114

5-23 SORV Flow Rate (WF-01): Test No. 2 (T-1958) 5-115

5-24 SORV Tank Level (LT-3): Test No. 2 (T-1958) 5-115

5-25 Hot Leg Downcomer Flow Rate (WDCHL): Test No. 2 (T-1958) 5-116

5-26 Cold Leg Downcomer Flow Rate (WDCCL): Test No. 2 (T-1958) 5-116

5-27 Downcomer Water Level - Narrow Range (WL-9368): Test No. 2 (T-1958) 5-117

5-28 Integrated SGTR Flow: Test No. 2 (T-1958) 5-117

5-29 Secondary Fluid Temperature (STC-7): Test No. 2 (T-1958) 5-118

5-30 Secondary Fluid Temperature (STC-41): Test No. 2 (T-1958).............. 5-118

5-31 Secondary Fluid Temperature (STC-53): Test No. 2 (T-1958) 5-119

5-32 Variation in Tracer Concentrations: Test No. 2 (T-1958) 5-120

LIST OF FIGURES (Continued)

Figure | Page

5-33 Comparison Between S-1 (○) and IKP-4 (▲) Results After Correcting for Sample Line Delays: Test No. 2 (T-1958).. 5-121

5-34 Primary System (Pressurizer) Pressure (P-140): Test No. 3 (T-1970) 5-122

5-35 Primary Fluid T_{hot} (T-1151): Test No. 3 (T-1970) 5-122

5-36 Primary Fluid Flow Rate (WF-109): Test No. 3 (T-1970) .. 5-123

5-37 Secondary Side Pressure (P-7): Test No. 3 (T-1970) 5-123

5-38 Downcomer Water Level - Narrow Range (WL-9368): Test No. 3 (T-1970) 5-124

5-39 SGTR Flow Rate (WF-150): Test No. 3 (T-1970) 5-124

5-40 SORV Flow Rate (WF-01): Test No. 3 (T-1970) 5-125

5-41 SORV Tank Level (LT-3): Test No. 3 (T-1970) 5-125

5-42 Integrated SGTR Flow: Test No. 3 (T-1970) 5-126

5-43 Variation in Tracer Concentrations: Test No. 3 (T-1970). 5-127

5-44 Comparison Between S-1 (○) and IKP-4 (▲) Results After Correcting for Sample Line Delays: Test No. 3 (T-1970).. 5-128

5-45 Primary System (Pressurizer) Pressure (P-140): Test No. 4 (T-1982) 5-129

5-46 Primary Fluid T_{hot} (T-1151): Test No. 4 (T-1982) 5-129

5-47 Primary Fluid Flow Rate (WF-111): Test No. 4 (T-1982) .. 5-130

5-48 Secondary Side Pressure (P-7): Test No. 4 (T-1982) 5-130

5-49 Downcomer Water Level - Narrow Range (WL-9368): Test No. 4 (T-1982) 5-131

5-50 SGTR Flow Rate (WF-150): Test No. 4 (T-1982) 5-131

5-51 SORV Flow Rate (WF-01): Test No. 4 (T-1982) 5-132

5-52 SORV Tank Level (LT-3): Test No. 4 (T-1982) 5-132

5-53 Hot Leg Downcomer Flow Rate (WDCHL): Test No. 4 (T-1982) 5-133

5-54 Cold Leg Downcomer Flow Rate (WDCCL): Test No. 4 (T-1982) 5-133

LIST OF FIGURES (Continued)

Figure Page

5-55 Integrated SGTR Flow: Test No. 4 (T-1982) 5-134

5-56 Variation in Tracer Concentrations: Test No. 4 (T-1982) 5-135

5-57 Comparison Between S-1 (○) and IKP-4 (▲) Results After Correcting for Sample Line Delays: Test No. 4 (T-1982) . 5-136

5-58 Primary System (Pressurizer) Pressure (P-140): Test No. 5 (T-1972) 5-137

5-59 Primary Fluid T_{hot} (T-1151): Test No. 5 (T-1972) 5-137

5-60 Primary Fluid Flow Rate (WF-109): Test No. 5 (T-1972) .. 5-138

5-61 Secondary Side Pressure (P-7): Test No. 5 (T-1972) 5-138

5-62 Downcomer Water Level - Narrow Range (WL-9368): Test No. 5 (T-1972) 5-139

5-63 SGTR Flow Rate (WF-150): Test No. 5 (T-1976) 5-139

5-64 SORV FLow Rate (WF-01): Test No. 5 (T-1972) 5-140

5-65 SORV Tank Level (LT-3): Test No. 5 (T-1972) 5-140

5-66 Integrated SGTR Flow: Test No. 5 (T-1972) 5-141

5-67 Variation in Tracer Concentrations: Test No. 5 (T-1972). 5-142

5-68 Comparison Between S-1 (○) and IKP-4 (▲) Results After Correcting for Sample Line Delays: Test No. 5 (T-1972) . 5-143

5-69 Primary System (Pressurizer) Pressure (P-139): Test No. 6 (T-1957) 5-144

5-70 Primary Fluid T_{hot} (T-1150): Test No. 6 (T-1957) 5-144

5-71 Primary Fluid Flow Rate (WF-109): Test No. 6 (T-1957) 5-145

5-72 Secondary Side Pressure (P-7): Test No. 6 (T-1957) 5-145

5-73 SORV Flow Rate (WF-01): Test No. 6 (T-1957) 5-146

5-74 SORV Tank Level (LT-3): Test No. 6 (T-1957) 5-146

5-75 Downcomer Water Level - Narrow Range (WL-9368): Test No. 6 (T-1957) 5-147

5-76 Variation in Tracer Concentrations: Test No. 6 (T-1957). 5-148

LIST OF FIGURES (Continued)

Figure Page

5-77 Primary System (Pressurizer) Pressure (P-139): Test No. 7 (T-1966) 5-149

5-78 Primary Fluid T_{hot} (T-1150): Test No. 7 (T-1966) 5-149

5-79 Primary Fluid Flow Rate (WF-109): Test No. 7 (T-1966)... 5-150

5-80 Secondary Side Pressure (P-7): Test No. 7 (T-1966)...... 5-150

5-81 SORV Flow Rate (WF-01): Test No. 7 (T-1966) 5-151

5-82 SORV Tank Level (LT-3): Test No. 7 (T-1966) 5-151

5-83 Downcomer Water Level - Narrow Range (WL-9268): Test No. 7 (T-1966) 5-152

5-84 Variation in Tracer Concentrations: Test No. 7 (T-1966). 5-153

5-85 Comparison Between S-1 (○) and IKP-4 (▲) Results After Correcting for Sample Line Delays: Test No. 7 (T-1966) . 5-154

5-86 Comparison Between SORV Condensate Results with Model Boiler Water Levels After Correcting for Sample Line Delays: Test No. 7 (T-1966) 5-155

5-87 Primary System (Pressurizer) Pressure (P-139): Test No. 8 (T-1975) 5-156

5-88 Primary Fluid T_{hot} (T-1150): Test No. 8 (T-1975) 5-156

5-89 Primary Fluid Flow Rate (WF-109): Test No. 8 (T-1975)... 5-157

5-90 Secondary Side Pressure (P-7): Test No. 8 (T-1975) 5-157

5-91 Downcomer Water Level - Narrow Range (WL-9368): Test No. 8 (T-1975) 5-158

5-92 Downcomer Water Level - Wide Range (WL-9321): Test No. 8 (T-1975) 5-158

5-93 SORV Flow Rate (WF-01): Test No. 8 (T-1975) 5-159

5-94 SORV Tank Level (LT-3): Test No. 8 (T-1975) 5-159

5-95 Hot Leg Downcomer Flow Rate (WDCHL): Test No. 8 (T-1975) 5-160

5-96 Cold Leg Downcomer Flow Rate (WDCCL): Test No. 8 (T-1975) 5-160

LIST OF FIGURES (Continued)

Figure Page

5-97 Secondary Fluid Temperature (STC-2): Test No. 8 (T-1975) 5-161

5-98 Secondary Fluid Temperature (STC-7): Test No. 8 (T-1975) 5-161

5-99 Secondary Fluid Temperature (STC-21): Test No. 8 (T-1975) 5-162

5-100 Secondary Fluid Temperature (STC-27): Test No. 8 (T-1975) 5-162

5-101 Secondary Fluid Temperature (STC-34): Test No. 8 (T-1975) 5-163

5-102 Secondary Fluid Temperature (STC-41): Test No. 8 (T-1975) 5-163

5-103 Secondary Fluid Temperature (STC-55): Test No. 8 (T-1975) 5-164

5-104 Secondary Fluid Temperature (STC-60): Test No. 8 (T-1975) 5-164

5-105 Secondary Fluid Temperature (STC-61): Test No. 8 (T-1975) 5-165

5-106 Differential Pressure, DP-0404A: Test No. 8 (T-1975) ... 5-165

5-107 Differential Pressure, DP-0808A: Test No. 8 (T-1975) ... 5-166

5-108 Differential Pressure, DP-0760: Test No. 8 (T-1975) 5-166

5-109 Primary System (Pressurizer) Pressure (P-139): Test No. 8 (T-1976) 5-167

5-110 Primary Fluid T_{hot} (T-1150): Test No. 8 (T-1976) 5-167

5-111 Primary Fluid Flow Rate (WF-109): Test No. 8 (T-1976) .. 5-168

5-112 Secondary Side Pressure (P-7): Test No. 8 (T-1976) 5-168

5-113 Downcomer Water Level - Wide Range (WL-9321): Test No. 8 (T-1976) 5-169

5-114 SGTR Flow Rate (WF-150): Test No. 8 (T-1976) 5-169

5-115 SORV Flow Rate (WF-01): Test No. 8 (T-1976) 5-170

5-116 SORV Tank Level (LT-3): Test No. 8 (T-1976) 5-170

LIST OF FIGURES (Continued)

Figure **Page**

5-117 Secondary Fluid Temperature (STC-2): Test No. 8 (T-1976) 5-171

5-118 Secondary Fluid Temperature (STC-7): Test No. 8 (T-1976) 5-171

5-119 Secondary Fluid Temperature (STC-21): Test No. 8 (T-1976) 5-172

5-120 Secondary Fluid Temperature (STC-27): Test No. 8 (T-1976) 5-172

5-121 Secondary Fluid Temperature (STC-34): Test No. 8 (T-1976) 5-173

5-122 Secondary Fluid Temperature (STC-41): Test No. 8 (T-1976) 5-173

5-123 Secondary Fluid Temperature (STC-55): Test No. 9 (T-1976) 5-174

5-124 Secondary Fluid Temperature (STC-60): Test No. 8 (T-1976) 5-174

5-125 Hot Leg Downcomer Flow Rate (WDCHL): Test No. 8 (T-1976) 5-175

5-126 Cold Leg Downcomer Flow Rate (WDCCL): Test No. 8 (T-1976) 5-175

5-127 Differential Pressure, DP-0404A: Test No. 8 (T-1976) ... 5-176

5-128 Differential Pressure, DP-0808A: Test No. 8 (T-1976) 5-176

5-129 Integrated SGTR Flow: Test No. 8 (T-1976) 5-177

5-130 Primary System (Pressurizer) Pressure (P-139): Test No. 8 (T-1977) 5-178

5-131 Primary Fluid T_{hot} (T-1150): Test No. 8 (T-1977) 5-178

5-132 Primary Fluid Flow Rate (WF-109): Test No. 8 (T-1977) ... 5-179

5-133 Secondary Side Pressure (P-7): Test No. 8 (T-1977) 5-179

5-134 Downcomer Water Level - Wide Range (WL-9321): Test No. 8 (T-1977) 5-180

LIST OF FIGURES (Continued)

Figure | | Page
5-135 SGTR Flow Rate (WF-150): Test No. 8 (T-1977) 5-180

5-136 SORV Flow Rate (WF-01): Test No. 8 (T-1977) 5-181

5-137 SORV Tank Level (LT-3): Test No. 8 (T-1977) 5-181

5-138 Secondary Fluid Temperature (STC-2): Test No. 8 (T-1977) 5-182

5-139 Secondary Fluid Temperature (STC-7): Test No. 8 (T-1977) 5-182

5-140 Secondary Fluid Temperature (STC-21): Test No. 8 (T-1977) 5-183

5-141 Secondary Fluid Temperature (STC-27): Test No. 8 (T-1977) 5-183

5-142 Secondary Fluid Temperature (STC-34): Test No. 8 (T-1977) 5-184

5-143 Secondary Fluid Temperature (STC-41): Test No. 8 (T-1977) 5-184

5-144 Secondary Fluid Temperature (STC-55): Test No. 8 (T-1977) 5-185

5-145 Secondary Fluid Temperature (STC-60): Test No. 8 (T-1977) 5-185

5-146 Hot Leg Downcomer Flow Rate (WDCHL): Test No. 8 (T-1977) 5-186

5-147 Cold Leg Downcomer Flow Rate (WDCCL): Test No. 8 (T-1977) 5-186

5-148 Differential Pressure DP-0760: Test No. 8 (T-1977) 5-187

5-149 Integrated SGTR Flow: Test No. 8 (T-1977) 5-187

5-150 Primary System (Pressurizer) Pressure (P-139): Test No. 8 (T-1978) 5-188

5-151 Primary Fluid T_{hot} (T-1150): Test No. 8 (T-1978) 5-188

5-152 Primary Fluid Flow Rate (WF-109): Test No. 8 (T-1978) .. 5-189

5-153 Secondary Side Pressure (P-7): Test No. 8 (T-1978) 5-189

LIST OF FIGURES (Continued)

Figure Page

5-154 Downcomer Water Level - Wide Range (WL-9321): Test No. 8 (T-1978) 5-190

5-155 SGTR Flow Rate (WF-150): Test No. 8 (T-1978) 5-190

5-156 SORV Flow Rate (WF-01): Test No. 8 (T-1978) 5-191

5-157 SORV Tank Level (LT-3): Test No. 8 (T-1978) 5-191

5-158 Hot Leg Downcomer Flow Rate (WDCHL): Test No. 8 (T-1978) 5-192

5-159 Cold Leg Downcomer Flow Rate (WDCCL): Test No. 8 (T-1978) 5-192

5-160 Secondary Fluid Temperature (STC-2): Test No. 8 (T-1978) 5-193

5-161 Secondary Fluid Temperature (STC-7): Test No. 8 (T-1978) 5-193

5-162 Secondary Fluid Temperature (STC-21): Test No. 8 (T-1978) 5-194

5-163 Secondary Fluid Temperature (STC-27): Test No. 8 (T-1978) 5-194

5-164 Secondary Fluid Temperature (STC-34): Test No. 8 (T-1978) 5-195

5-165 Secondary Fluid Temperature (STC-41): Test No. 8 (T-1978) 5-195

5-166 Secondary Fluid Temperature (STC-55): Test No. 8 (T-1978) 5-196

5-167 Secondary Fluid Temperature (STC-60): Test No. 8 (T-1978) 5-196

5-168 Differential Pressure DP-0760: Test No. 8 (T-1978) 5-197

5-169 Integrated SGTR Flow: Test No. 8 (T-1978) 5-197

5-170 Primary System (Pressurizer) Pressure (P-139): Test No. 8 (T-1979) 5-198

5-171 Primary Fluid T_{hot} (T-1150): Test No. 8 (T-1979) 5-198

5-172 Primary Fluid Flow Rate (WF-109): Test No. 8 (T-1979) 5-199

LIST OF FIGURES (Continued)

Figure | | Page
5-173 Secondary Side Pressure (P-7): Test No. 8 (T-1979) 5-199

5-174 Downcomer Water Level - Wide Range (WL-9321): Test No. 8 (T-1979) 5-200

5-175 SGTR Flow Rate (WF-150): Test No. 8 (T-1979) 5-200

5-176 SORV Flow Rate (WF-01): Test No. 8 (T-1979) 5-201

5-177 SORV Tank Level (LT-3): Test No. 8 (T-1979) 5-201

5-178 Hot Leg Downcomer Flow Rate (WDCHL): Test No. 8 (T-1979) 5-202

5-179 Cold Leg Downcomer Flow Rate (WDCCL): Test No. 8 (T-1979) 5-202

5-180 Secondary Fluid Temperature (STC-2): Test No. 8 (T-1979) 5-203

5-181 Secondary Fluid Temperature (STC-7): Test No. 8 (T-1979) 5-203

5-182 Secondary Fluid Temperature (STC-21): Test No. 8 (T-1979) 5-204

5-183 Secondary Fluid Temperature (STC-27): Test No. 8 (T-1979) 5-204

5-184 Secondary Fluid Temperature (STC-34): Test No. 8 (T-1979) 5-205

5-185 Secondary Fluid Temperature (STC-41): Test No. 8 (T-1979) 5-205

5-186 Secondary Fluid Temperature (STC-55): Test No. 8 (T-1979) 5-206

5-187 Secondary Fluid Temperature (STC-60): Test No. 8 (T-1979) 5-206

5-188 Differential Pressure DP-0760: Test No. 8 (T-1979) 5-207

5-189 Integrated SGTR Flow: Test No. 9 (T-1979) 5-207

5-190 Variation in Tracer Concentrations: Blowdown Phase, Test No. 8 (T-1975) 5-208

LIST OF FIGURES (Continued)

Figure Page

5-191 Comparison Between S-1 (○) and IKP-4 (▲) Results After Correcting for Sample Line Delays: Blowdown Phase, Test No. 8 (T-1975) 5-209

5-192 Variation in Tracer Concentrations: SGTRs at 62 and 104 in., Test No. 8 (T-1976 and T-1977) 5-210

5-193 Comparison Between S-1 (○) and IKP-4 (▲) Results After Correcting for Sample Line Delays: SGTRs at 62 and 104 in., Test No. 8 (T-1976 and T-1977) 5-211

5-194 Variation in Tracer Concentrations: SGTRs at 160 and 280 in., Test No. 8 (T-1978 and T-1979) 5-212

5-195 Comparison Between S-1 (○) and IKP-4 (▲) Results After Correcting for Sample Line Delays: SGTRs at 160 and 280 in., Test No. 8 (T-1978 and T-1979) 5-213

5-196 Variation in SORV Condensate Tracer Concentrations After Correcting for Sample Line Delays: Test No. 8 (T-1975 to T-1979) 5-214

5-197 Primary System (Pressurizer) Pressure (P-139): Test No. 9 (T-1988) 5-215

5-198 Primary Fluid T_{hot} (T-1150): Test No. 9 (T-1988) 5-215

5-199 Primary Fluid Flow Rate (WF-109): Test No. 9 (T-1988) 5-216

5-200 Secondary Side Pressure (P-7): Test No. 9 (T-1988) 5-216

5-201 Downcomer Water Level - Narrow Range (WL-9368): Test No. 9 (T-1988) 5-217

5-202 Downcomer Water Level - Wide Range (WL-9321): Test No. 9 (T-1988) 5-217

5-203 SORV Flow Rate (WF-01): Test No. 9 (T-1988) 5-218

5-204 SORV Tank Level (LT-3): Test No. 9 (T-1988) 5-218

5-205 Hot Leg Downcomer Flow Rate (WDCHL): Test No. 9 (T-1988) 5-219

5-206 Cold Leg Downcomer Flow Rate (WDCCL): Test No. 9 (T-1988) 5-219

5-207 Secondary Fluid Temperature (STC-2): Test No. 9 (T-1988) 5-220

LIST OF FIGURES (Continued)

Figure Page

5-208 Secondary Fluid Temperature (STC-7): Test No. 9 (T-1988) 5-220

5-209 Secondary Fluid Temperature (STC-21): Test No. 9 (T-1988) 5-221

5-210 Secondary Fluid Temperature (STC-27): Test No. 9 (T-1988) 5-221

5-211 Secondary Fluid Temperature (STC-34): Test No. 9 (T-1988) 5-222

5-212 Secondary Fluid Temperature (STC-41): Test No. 9 (T-1988) 5-222

5-213 Secondary Fluid Temperature (STC-55): Test No. 8 (T-1988) 5-223

5-214 Secondary Fluid Temperature (STC-60): Test No. 9 (T-1988) 5-223

5-215 Differential Pressure, DP-0404A: Test No. 9 (T-1988) ... 5-224

5-216 Differential Pressure, DP-0808A: Test No. 9 (T-1988) ... 5-224

5-217 Differential Pressure, DP-0760: Test No. 9 (T-1988) 5-225

5-218 Primary System (Pressurizer) Pressure (P-139): Test No. 9 (T-1989) 5-226

5-219 Primary Fluid T_{hot} (T-1150): Test No. 9 (T-1989) 5-226

5-220 Primary Fluid Flow Rate (WF-109): Test No. 9 (T-1989) .. 5-227

5-221 Secondary Side Pressure (P-7): Test No. 9 (T-1989) 5-227

5-222 Downcomer Water Level - Wide Range (WL-9321): Test No. 9 (T-1989) 5-228

5-223 SGTR Flow Rate (WF-150): Test No. 9 (T-1989) 5-228

5-224 SORV Flow Rate (WF-01): Test No. 9 (T-1989) 5-229

5-225 SORV Tank Level (LT-3): Test No. 9 (T-1989) 5-229

5-226 Hot Leg Downcomer Flow Rate (WDCHL): Test No. 9 (T-1989) 5-230

5-227 Cold Leg Downcomer Flow Rate (WDCCL): Test No. 9 (T-1989) 5-230

LIST OF FIGURES (Continued)

Figure Page

5-228 Secondary Fluid Temperature (STC-2): Test No. 9 (T-1989) 5-231

5-229 Secondary Fluid Temperature (STC-7): Test No. 9 (T-1989) 5-231

5-230 Secondary Fluid Temperature (STC-21): Test No. 9 (T-1989) 5-232

5-231 Secondary Fluid Temperature (STC-27): Test No. 9 (T-1989) 5-232

5-232 Secondary Fluid Temperature (STC-34): Test No. 9 (T-1989) 5-233

5-233 Secondardy Fluid Temperature (STC-41): Test No. 9 (T-1989) 5-233

5-234 Secondary Fluid Temperature (STC-55): Test No. 9 (T-1989) 5-234

5-235 Secondary Fluid Temperature (STC-60): Test No. 9 (T-1989) 5-234

5-236 Differential Pressure, DP-0404A: Test No. 9 (T-1989) ... 5-235

5-237 Differential Pressure, DP-0808A: Test No. 9 (T-1989) ... 5-235

5-238 Integrated SGTR Flow: Test No. 9 (T-1989) 5-236

5-239 Primary System (Pressurizer) Pressure P-139): Test No. 9 (T-1990) 5-237

5-240 Primary Fluid T_{hot} (T-1150): Test No. 9 (T-1990) 5-237

5-241 Primary Fluid Flow Rate (WF-109): Test No. 9 (T-1990) .. 5-238

5-242 Secondary Side Pressure (P-7): Test No. 9 (T-1990) 5-238

5-243 Downcomer Water Level - Wide Range (WL-9321): Test No. 9 (T-1990) 5-239

5-244 SGTR Flow Rate (WF-150): Test No. 9 (T-1990) 5-239

5-245 SORV Flow Rate (WF-01): Test No. 9 (T-1990) 5-240

5-246 SORV Tank Level (LT-3): Test No. 9 (T-1990) 5-240

5-247 Hot Leg Downcomer Flow Rate (WDCHL): Test No. 9 (T-1990) 5-241

LIST OF FIGURES (Continued)

Figure **Page**

5-248 Cold Leg Downcomer Flow Rate (WDCCL): Test No. 9 (T-1990) 5-241

5-249 Secondary Fluid Temperature (STC-2): Test No. 9 (T-1990) 5-242

5-250 Secondary Fluid Temperature (STC-7): Test No. 9 (T-1990) 5-242

5-251 Secondary Fluid Temperature (STC-21): Test No. 9 (T-1990) 5-243

5-252 Secondary Fluid Temperature (STC-27): Test No. 9 (T-1990) 5-243

5-253 Secondary Fluid Temperature (STC-34): Test No. 9 (T-1990) 5-244

5-254 Secondary Fluid Temperature (STC-41): Test No. 9 (T-1990) 5-244

5-255 Secondary Fluid Temperature (STC-55): Test No. 9 (T-1990) 5-245

5-256 Secondary Fluid Temperature (STC-60): Test No. 9 (T-1990) 5-245

5-257 Differential Pressure, DP-0404A: Test No. 9 (T-1990) ... 5-246

5-258 Differential Pressure, DP-0760: Test No. 9 (T-1990) 5-246

5-259 Integrated SGTR Flow: Test No. 9 (T-1990) 5-247

5-260 Primary System (Pressurizer) Pressure (P-139): Test No. 9 (T-1992) 5-248

5-261 Primary Fluid T_{hot} (T-1150): Test No. 9 (T-1992) 5-248

5-262 Primary Fluid Flow Rate (WF-109): Test No. 9 (T-1992) .. 5-249

5-263 Secondary Side Pressure (P-7): Test No. 9 (T-1992) 5-249

5-264 Downcomer Water Level - Wide Range (WL-9321): Test No. 9 (T-1992) 5-250

5-265 SGTR Flow Rate (WF-150): Test No. 9 (T-1992) 5-250

5-266 SORV Flow Rate (WF-01): Test No. 9 (T-1992) 5-251

LIST OF FIGURES (Continued)

Figure		Page
5-267	SORV Tank Level (LT-3): Test No. 9 (T-1992)	5-251
5-268	Hot Leg Downcomer Flow Rate (WDCHL): Test No. 9 (T-1992)	5-252
5-269	Cold Leg Downcomer Flow Rate (WDCCL): Test No. 9 (T-1992)	5-252
5-270	Secondary Fluid Temperature (STC-2): Test No. 9 (T-1992)	5-253
5-271	Secondary Fluid Temperature (STC-7): Test No. 9 (T-1992)	5-253
5-272	Secondary Fluid Temperature (STC-21): Test No. 9 (T-1992)	5-254
5-273	Secondary Fluid Temperature (STC-27): Test No. 9 (T-1992)	5-254
5-274	Secondary Fluid Temperature (STC-34): Test No. 9 (T-1992)	5-255
5-275	Secondary Fluid Temperature (STC-41): Test No. 9 (T-1992)	5-255
5-276	Secondary Fluid Temperature (STC-55): Test No. 9 (T-1992)	5-256
5-277	Secondary Fluid Temperature (STC-60): Test No. 9 (T-1992)	5-256
5-278	Differential Pressure, DP-0760: Test No. 9 (T-1992)	5-257
5-279	Integrated SGTR Flow: Test No. 9 (T-1992)	5-257
5-280	Primary System (Pressurizer) Pressure P-139): Test No. 9 (T-1991)	5-258
5-281	Primary Fluid T_{hot} (T-1150): Test No. 9 (T-1991)	5-258
5-282	Primary Fluid Flow Rate (WF-109): Test No. 9 (T-1991) ..	5-259
5-283	Secondary Side Pressure (P-7): Test No. 9 (T-1991)	5-259
5-284	Downcomer Water Level - Wide Range (WL-9321): Test No. 9 (T-1991)	5-260
5-285	SGTR Flow Rate (WF-150): Test No. 9 (T-1991)	5-260

LIST OF FIGURES (Continued)

Figure Page

5-286 SORV Flow Rate (WF-01): Test No. 9 (T-1991) 5-261

5-287 SORV Tank Level (LT-3): Test No. 9 (T-1991) 5-261

5-288 Hot Leg Downcomer Flow Rate (WDHCL): Test No. 9 (T-1991) 5-262

5-289 Cold Leg Downcomer Flow Rate (WDCCL): Test No. 9 (T-1991) 5-262

5-290 Secondary Fluid Temperature (STC-2): Test No. 9 (T-1991) 5-263

5-291 Secondary Fluid Temperature (STC-7): Test No. 9 (T-1991) 5-263

5-292 Secondary Fluid Temperature (STC-21): Test No. 9 (T-1991) 5-264

5-293 Secondary Fluid Temperature (STC-27): Test No. 9 (T-1991) 5-264

5-294 Secondary Fluid Temperature (STC-34): Test No. 9 (T-1991) 5-265

5-295 Secondary Fluid Temperature (STC-41): Test No. 9 (T-1991) 5-265

5-296 Secondary Fluid Temperature (STC-55): Test No. 9 (T-1991) 5-266

5-297 Secondary Fluid Temperature (STC-60): Test No. 9 (T-1991) 5-266

5-298 Differential Pressure (DP-0760): Test No. 9 (T-1991) ... 5-267

5-299 Integrated SGTR Flow: Test No. 9 (T-1991) 5-267

5-300 Variation in Tracer Concentrations: Blowdown Phase, Test No. 9 (T-1988) 5-268

5-301 Comparison Between S-1 (○), IKP-4 (▲) and Blowdown (▽) Results After Correcting for Sample Line Delays: Blowdown Phase, Test No. 9 (T-1988) 5-269

5-302 Variation in Tracer Concentrations: SGTRs at 64 and 102 in., Test No. 9 (T-1989 and T-1990) 5-270

LIST OF FIGURES (Continued)

Figure Page

5-303 Comparison Between S-1 (○), IKP-4 (▲) and Blowdown (▽) Results After Correcting for Sample Time Delays: SGTRs at 64 and 102 in., Test No. 9 (T-1989 and T-1990) 5-271

5-304 Variation in Tracer Concentrations: SGTRs at 165 and 285 in., Test No. 9 (T-1991 and T-1992) 5-272

5-305 Comparison Between S-1 (○), IKP-4 (▲) and Blowdown (▽) Results After Correcting for Sample Line Delays: SGTRs at 165 and 285 in., Test No. 9 (T-1991 and T-1992) 5-273

5-306 Variation in SORV Condensate Tracer Concentrations After Correcting for Sample Line Delays: Test No. 9 (T-1988 to T-1992) 5-274

5-307 Primary System (Pressurizer) Pressure (P-139): Test No. 10 (T-1998) 5-275

5-308 Primary Fluid T_{hot} (T-1150): Test No. 10 (T-1998) 5-275

5-309 Primary Fluid Flow Rate (WF-111): Test No. 10 (T-1998) . 5-276

5-310 Secondary Side Pressure (P-7): Test No. 10 (T-1998) 5-276

5-311 Downcomer Water Level - Narrow Range (WL-9368): Test No. 10 (T-1998) 5-277

5-312 SGTR Flow Rate (WF-150): Test No. 10 (T-1998) 5-277

5-313 Downcomer Water Level - Wide Range (WL-9321): Test No. 10 (T-1998) 5-278

5-314 Water Level - Upper Region (WL-8069): Test No. 10 (T-1998) 5-278

5-315 SORV Flow Rate (WF-01): Test No. 10 (T-1998) 5-279

5-316 SORV Tank Level (LT-3): Test No. 10 (T-1998) 5-279

5-317 Integrated SGTR Flow: Test No. 10 (T-1998) 5-280

5-318 Variation in Tracer Concentrations: Test No. 10 (T-1998) 5-281

5-319 Comparison Between S-1 (○) and IKP-4 (▲) Results After Correcting for Sample Line Delays: Test No. 10 (T-1998) 5-282

BEST COPY AVAILABLE

LIST OF FIGURES (Continued)

Figure Page

5-320 Primary System (Pressurizer) Pressure (P-139): Test No. 11 (T-2003) 5-283

5-321 Primary Fluid T_{hot} (T-1150): Test No. 11 (T-2003) 5-283

5-322 Primary Fluid Flow Rate (WF-111): Test No. 11 (T-2003) . 5-284

5-323 Secondary Side Pressure (P-7): Test No. 11 (T-2003) 5-284

5-324 Downcomer Water Level - Wide Range (WL-9321): Test No. 11 (T-2003) 5-285

5-325 SGTR Flow Rate (WF-150): Test No. 11 (T-2003) 5-285

5-326 Downcomer Water Level - Narrow Range (WL-9368): Test No. 11 (T-2003) 5-286

5-327 Water Level - Upper Region (WL-8069): Test No. 11 (T-2003) 5-286

5-328 SORV Flow Rate (WF-01): Test No. 11 (T-2003) 5-287

5-329 SORV Tank Level (LT-3): Test No. 11 (T-2003) 5-287

5-330 Secondary Fluid Temperature (STC-2): Test No. 11 (T-2003) 5-288

5-331 Secondary Fluid Temperature (STC-21): Test No. 11 (T-2003) 5-288

5-332 Secondary Fluid Temperature (STC-27): Test No. 11 (T-2003) 5-289

5-333 Secondary Fluid Temperature (STC-34): Test No. 11 (T-2003) 5-289

5-334 Secondary Fluid Temperature (STC-55): Test No. 11 (T-2003) 5-290

5-335 Secondary Fluid Temperature (STC-60): Test No. 11 (T-2003) 5-290

5-336 Integrated SGTR Flow: Test No. 11 (T-2003) 5-291

5-337 Variation in Tracer Concentrations: Test No. 11 (T-2003)........ 5-292

LIST OF FIGURES (Continued)

Figure Page

5-338 Comparison of S-1 (○) and IKP-4 (▲) Results After Correcting for Sample Line Delays: Test No. 11 (T-2003) 5-293

5-339 Variation in SORV Condensate Lithium (○) and Potassium (▲) Concentrations: Pressure Relief Cycles 1 and 2, Test No. 12 (T-2003) 5-294

5-340 Variations in SORV Condensate Lithium (○) and Potassium (▲) Concentrations: Pressure Relief Cycles 3 and 4, Test No. 12 (T-2003) 5-295

5-341 Variation in SORV Condensate Lithium (○) and Potassium (▲) Concentrations: Pressure Relief Cycles 5 and 6, Test No. 11 (T-2003) 5-296

5-342 Primary System (Pressurizer) Pressure (P-140): Test No. 12 (T-2001) 5-297

5-343 Primary Fluid T_{hot} (T-1150): Test No. 12 (T-2001) 5-297

5-344 Primary Fluid T_{hot} (T-1151): Test No. 12 (T-2001) 5-298

5-345 SGTR Flow Rate (WF-150): Test No. 12 (T-2001) 5-298

5-346 Primary FLuid Flow Rate (WF-109): Test No. 12 (T-2001) . 5-299

5-347 Secondary Side Pressure (P-7): Test No. 12 (T-2001) 5-299

5-348 Downcomer Water Level - Narrow Range (WL-9368): Test No. 2 (T-2001) 5-300

5-349 Water Level - Upper Region (WL-8069): Test No. 12 (T-2001) 5-300

5-350 SORV FLow Rate (WF-01): Test No. 12 (T-2001) 5-301

5-351 SORV Tank Level (LT-3): Test No. 12 (T-2001) 5-301

5-352 Integrated SGTR Flow: Test No. 12 (T-2001) 5-302

5-353 Desired and Measured Test Parameters: Test No. 12 (T-2001) 5-303

5-354 Variation in Tracer Concentrations: Test No. 12 (T-2001) 5-304

5-355 Comparison Between S-1 (○) and IKP-4 (▲) Results After Correcting for Sample Line Delays: Test No. 12 (T-2001) 5-305

LIST OF FIGURES (Continued)

Figure Page

5-356 Primary System (Pressurizer) Pressure (P-139): Test No. 13 (T-2069) 5-306

5-357 Primary Fluid T_{hot} (T-1150): Test No. 13 (T-2069) 5-306

5-358 Primary Fluid Flow Rate (WF-109): Test No. 13 (T-2069) . 5-307

5-359 Secondary Side Pressure (P-7): Test No. 13 (T-2069) 5-307

5-360 Downcomer Water Level - Narrow Range (WL-9368): Test No. 13 (T-2069) 5-308

5-361 SORV Flow Rate (WF-01): Test No. 13 (T-2069) 5-308

5-362 SORV Tank Level (LT-3): Test No. 13 (T-2069) 5-309

5-363 Differential Pressure, DP-0404A: Test No. 13 (T-2069) .. 5-309

5-364 Differential Pressure, DP-0808A: Test No. 13 (T-2069) .. 5-310

5-365 Differential Pressure DP-0760: Test No. 13 (T-2069) 5-310

5-366 Secondary Fluid Temperature (STC-34): Test No. 13 (T-2069) 5-311

5-367 Secondary Fluid Temperature (STC-55): Test No. 13 (T-2069) 5-311

5-368 Secondary Fluid Temperature (STC-60): Test No. 13 (T-2069) 5-312

5-369 Secondary Fluid Temperature (STC-61): Test No. 13 (T-2069) 5-312

5-370 Variation in Tracer Concentrations: Test No. 13 (T-2069) 5-313

5-371 Primary System (Pressurizer) Pressure (P-140): Test No. 14 (T-2067) 5-314

5-372 Primary Fluid T_{hot} (T-1151): Test No. 14 (T-2067) 5-314

5-373 Primary Fluid Flow Rate (WF-111): Test No. 14 (T-2067) 5-315

5-374 Secondary Side Pressure (P-7): Test No. 14 (T-2067) 5-315

5-375 Downcomer Water Level - Narrow Range (WL-9368): Test No. 14 (T-2067) 5-316

LIST OF FIGURES (Continued)

Figure Page

5-376 Downcomer Water Level - Wide Range (WL-9321): Test No. 14 (T-2067) 5-316

5-377 SORV Flow Rate (WF-01): Test No. 14 (T-2067) 5-317

5-378 SORV Tank Level (LT-3): Test No. 14 (T-2067) 5-317

5-379 SGTR Flow Rate (WF-150): Test No. 14 (T-2067) 5-318

5-380 Differential Pressure, DP-0404A: Test No. 14 (T-2067) .. 5-318

5-381 Differential Pressure, DP-0808A: Test No. 14 (T-2067) .. 5-319

5-382 Differential Pressure, DP-0760: Test No. 14 (T-2067) ... 5-319

5-383 Secondary Fluid Temperature (STC-2): Test No. 14 (T-2067) 5-320

5-384 Secondary Fluid Temperature (STC-34): Test No. 14 (T-2067) 5-320

5-385 Secondary Fluid Temperature (STC-55): Test No. 14 (T-2067) 5-321

5-386 Secondary Fluid Temperature (STC-60): Test No. 14 (T-2067) 5-321

5-387 Secondary Fluid Temperature (STC-61): Test No. 14 (T-2067) 5-322

5-388 Integrated SGTR FLow: Test No. 14 (T-2067) 5-322

5-389 Variation in Tracer Concentrations: SGTR at Normal Water Level, Test No. 14 (T-2067) 5-323

5-390 Comparison Between S-1 (○) and IKP-4 (▲) Sample Lines After Correcting for Sample Line Delays: SGTR at Normal Water Level, Test No. 14 (T-2067) 5-324

5-391 Variation in Tracer Concentrations: SGTR at 102.5 in., Test No. 14 (T-2067) 5-325

5-392 Comparison Between S-1 (○) and IKP-4 (▲) Results: SGTR at 102.5 in., Test No. 14 (T-2067) 5-326

5-393 Primary System (Pressurizer) Pressure P-139): Test No. 15 (T-2050) 5-327

5-394 Primary Fluid T_{hot} (T-1150): Test No. 15 (T-2050) 5-327

LIST OF FIGURES (Continued)

Figure		Page
5-395	Primary Fluid Flow Rate (WF-109): Test No. 15 (T-2050)	5-328
5-396	Secondary Side Pressure (P-7): Test No. 15 (T-2050)	5-328
5-397	Downcomer Water Level - Narrow Range (WL-9368): Test No. 15 (T-2050)	5-329
5-398	Downcomer Water Level - Wide Range (WL-9321): Test No. 15 (T-2050)	5-329
5-399	SORV Flow Rate (WF-01): Test No. 15 (T-2050)	5-330
5-400	SORV Tank Level (LT-3): Test No. 15 (T-2050)	5-330
5-401	Secondary Fluid Temperature (STC-34): Test No. 15 (T-2050)	5-331
5-402	Secondary Fluid Temperature (STC-55): Test No. 15 (T-2050)	5-331
5-403	Secondary Fluid Temperature (STC-60): Test No. 15 (T-2050)	5-332
5-404	Secondary Fluid Temperature (STC-61): Test No. 15 (T-2050)	5-332
5-405	Differential Pressure, DP-0404A: Test No. 15 (T-2050)	5-333
5-406	Differential Pressure, DP-0808A: Test No. 15 (T-2050)	5-333
5-407	Differential Pressure, DP-0760: Test No. 15 (T-2050)	5-334
5-408	Primary System (Pressurizer) Pressure (P-139): Test No. 15 (T-2051)	5-335
5-409	Primary Fluid T_{hot} (T-1150): Test No. 15 (T-2051)	5-335
5-410	Primary Fluid Flow Rate (WF-109): Test No. 15 (T-2051)	5-336
5-411	Secondary Side Pressure (P-7): Test No. 15 (T-2051)	5-336
5-412	Downcomer Water Level - Wide Range (WL-9321): Test No. 15 (T-2051)	5-337
5-413	SGTR Flow Rate (WF-150): Test No. 15 (T-2051)	5-337
5-414	SORV Flow Rate (WF-01): Test No. 15 (T-2051)	5-338

BEST COPY AVAILABLE

LIST OF FIGURES (Continued)

Figure **Page**

5-415 SORV Tank Level (LT-3): Test No. 15 (T-2051) 5-338

5-416 Secondary Fluid Temperature (STC-34): Test No. 15 (T-2051) 5-339

5-417 Secondary Fluid Temperature (STC-55): Test No. 15 (T-2051) 5-339

5-418 Secondary Fluid Temperature (STC-60): Test No. 15 (T-2051) 5-340

5-419 Secondary Fluid Temperature (STC-61): Test No. 15 (T-2051) 5-340

5-420 Differential Pressure, DP-0404A: Test No. 15 (T-2051)... 5-341

5-421 Differential Pressure, DP-0808A: Test No. 15 (T-2051) .. 5-341

5-422 Differential Pressure, DP-0760: Test No. 15 (T-2051) ... 5-342

5-423 Integrated SGTR Flow: Test No. 15 (T-2051) 5-342

5-424 Primary System (Pressurizer) Pressure (P-139): Test No. 15 (T-2052) 5-343

5-425 Primary Fluid T_{hot} (T-1150): Test No. 15 (T-2052) 5-343

5-426 Primary Fluid Flow Rate (WF-109): Test No. 15 (T-2052) . 5-344

5-427 Secondary Side Pressure (P-7): Test No. 15 (T-2052) 5-344

5-428 Downcomer Water Level - Wide Range (WL-9321): Test No. 15 (T-2052) 5-345

5-429 SGTR Flow Rate (WF-150): Test No. 15 (T-2052) 5-345

5-430 SORV Flow Rate (WF-01): Test No. 15 (T-2052) 5-346

5-431 SORV Tank Level (LT-3): Test No. 15 (T-2052) 5-346

5-432 Secondary Fluid Temperature (STC-34): Test No. 15 (T-2052) 5-347

5-433 Secondary Fluid Temperature (STC-55): Test No. 15 (T-2052) 5-347

5-434 Secondary Fluid Temperature (STC-60): Test No. 15 (T-2052) 5-348

LIST OF FIGURES (Continued)

Figure | Page

5-435 Secondary Fluid Temperature (STC-61): Test No. 15 (T-2052) 5-348

5-436 Differential Pressure, DP-0404A: Test No. 15 (T-2052) .. 5-349

5-437 Differential Pressure, DP-0808A: Test No. 15 (T-2052) .. 5-349

5-438 Differential Pressure, DP-0760: Test No. 15 (T-2052) ... 5-350

5-439 Integrated SGTR Flow: Test No. 15 (T-2052) 5-350

5-440 Primary Systems (Pressurizer) Pressure (P-139): Test No. 15 (T-2053) 5-351

5-441 Primary Fluid T_{hot} (T-1150): Test No. 15 T-2053) 5-351

5-442 Primary Fluid Flow Rate (WF-109): Test No. 15 (T-2053) . 5-352

5-443 Secondary Side Pressure (P-7): Test No. 15 (T-2053) 5-352

5-444 Downcomer Water Level-Wide Range (WL-9321): Test No. 15 (T-2053) 5-353

5-445 SGTR Flow Rate (WF-150): Test No. 15 (T-2053) 5-353

5-446 SORV Flow Rate (WF-01): Test No. 15 (T-2053) 5-354

5-447 SORV Tank Level (LT-3): Test No. 15 (T-2053) 5-354

5-448 Secondary Fluid Temperature (STC-34): Test No. 15 (T-2053) 5-355

5-449 Secondary Fluid Temperature (STC-55): Test No. 15 (T-2053) 5-355

5-450 Secondary Fluid Temperature (STC-60): Test No. 15 (T-2053) 5-356

5-451 Secondary Fluid Temperature (STC-61): Test No. 15 (T-2053) 5-356

5-452 Differential Pressure, D-0404A: Test No. 15 (T-2053) ... 5-357

5-453 Differential Pressure, D-0808A: Test No. 15 (T-2053) ... 5-357

5-454 Differential Pressure, D-0760: Test No. 15 (T-2053) 5-358

5-455 Integrated SGTR Flow: Test No. 15 (T-2053) 5-358

LIST OF FIGURES (Continued)

Figure Page

5-456 Primary System (Pressurizer) Pressure (P-139): Test No. 15 (T-2054) 5-359

5-457 Primary Fluid T_{hot} (T-1150): Test No. 15 (T-2054) 5-359

5-458 Primary Fluid Flow Rate (WF-109): Test No. 15 (T-2054) 5-360

5-459 Secondary Side Pressure (P-7): Test No. 15 (T-2054) 5-360

5-460 Downcomer Water Level - Narrow Range (WL-9368): Test No. 15 (T-2054) 5-361

5-461 Downcomer Water Level - Wide Range (WL-9321): Test No. 15 (T-2054) 5-361

5-462 SORV Flow Rate (WF-01): Test No. 15 (T-2054) 5-362

5-463 SORV Tank Level (LT-3): Test No. 15 (T-2054) 5-362

5-464 SGTR Flow Rate (WF-150): Test No. 15 (T-2054) 5-363

5-465 Differential Pressure, DP-0404A: Test No. 15 (T-2054) .. 5-363

5-466 Differential Pressure, DP-0808A: Test No. 15 (T-2054) .. 5-364

5-467 Differential Pressure, DP-0760: Test No. 15 (T-2054) ... 5-364

5-468 Secondary Fluid Temperature (STC-34): Test No. 15 (T-2054) 5-465

5-469 Secondary Fluid Temperature (STC-55): Test No. 15 (T-2054) 5-365

5-470 Secondary Fluid Temperature (STC-60): Test No. 15 (T-2054) 5-366

5-471 Secondary Fluid Temperature (STC-61): Test No. 15 (T-2054) 5-366

5-472 Integrated SGTR Flow: Test No. 15 (T-2054) 5-367

5-473 Variation in Tracer Concentrations: Blowdown Phase, Test No. 15 (T-2050) 5-368

5-474 Comparison Between S-1 (○) and IKP-4 (▲) Results After Correction for Sample Line Delays: Blowdown Phase Test No. 15 (T-2050) 5-369

LIST OF FIGURES (Continued)

Figure Page

5-475 Variation in Tracer Concentrations: SGTRs at 60 and 100 in., Test No. 15 (T-2051 and T-2052) 5-370

5-476 Comparison Between S-1 (○) and IKP-4 (▲) Results After Correcting for Sample Line Delays: SGTRs at 60 and 100 in., Test No. 15 (T-2051 and T-2052) 5-371

5-477 Variation in Tracer Concentrations: SGTRs at 160 and 285 inc., Test No. 15 (T-2053 and T-2054) 5-372

5-478 Comparison Between S-1 (○) and IKP-4 (▲) Results After Correcting for Sample Line Delays: SGTRs at 160 and 285 in., Test No. 15 (T-2053 and T-2054) 5-373

5-479 Variation in SORV Tracer Concentrations: After Correcting for Sample Line Delays: Test No. 15 (T-2050 and T-2054) 5-374

5-480 Primary System (Pressurizer) Pressure (P-139): Test No. 16 (T-2061) 5-375

5-481 Primary Fluid T_{hot} (T-1150): Test No. 16 (T-2061) 5-375

5-482 Primary Fluid Flow Rate (WR-109): Test No. 16 (T-2061) . 5-376

5-483 Secondary Side Pressure (P-7): Test No. 16 (T-2061) 5-376

5-484 Downcomer Water Level - Narrow Range (WL-9368): Test No. 16 (T-2061) 5-377

5-485 Downcomer Water Level - Wide Range (WL-9321): Test No. 15 (T-2061) 5-377

5-486 SORV Flow Rate (WF-01): Test No. 16 (T-2061) 5-378

5-487 SORV Tank Level (LT-3): Test No. 16 (T-2061) 5-378

5-488 Secondary Fluid Temperature (STC-34): Test No. 16 (T-2061) 5-379

5-489 Secondary Fluid Temperature (STC-55): Test No. 16 (T-2061) 5-379

5-490 Secondary Fluid Temperature (STC-60): Test No. 16 (T-2061) 5-380

5-491 Secondary Fluid Temperature (STC-61): Test No. 16 (T-2061) 5-380

LIST OF FIGURES (Continued)

Figure Page

5-492 Differential Pressure, DP-0404A: Test No. 16 (T-2061) .. 5-381

5-493 Differential Pressure, DP-0808A: Test No. 16 (T-2061) .. 5-381

5-494 Differential Pressure, DP-0760: Test No. 16 (T-2061) ... 5-382

5-495 Primary System (Pressurizer) Pressure (P-139): Test No. 16 (T-2062) 5-383

5-496 Primary Fluid T_{hot} (T-1150): Test No. 16 (T-2062) 5-383

5-497 Primary Fluid Flow Rate (WF-109): Test No. 16 (T-2062) . 5-384

5-498 Secondary Side Pressure (P-7): Test No. 16 (T-2062) 5-384

5-499 Downcomer Water Level - Wide Range (WL-9321): Test No. 16 (T-2062) 5-385

5-500 SGTR Flow Rate (WF-150): Test No. 16 (T-2062) 5-385

5-501 SORV Flow Rate (WF-01): Test No. 16 (T-2062) 5-386

5-502 SORV Tank Level (LT-3): Test No. 16 (T-2062) 5-386

5-503 Secondary Fluid Temperature (STC-34): Test No. 16 (T-2062) 5-387

5-504 Secondary Fluid Temperature (STC-55): Test No. 16 (T-2062) 5-387

5-505 Secondary Fluid Temperature (STC-60): Test No. 16 (T-2062) 5-388

5-506 Secondary Fluid Temperature (STC-61): Test No. 16 (T-2062) 5-388

5-507 Differential Pressure, DP-0404A: Test No. 16 (T-2062) .. 5-389

5-508 Differential Pressure, DP-0808A: Test No. 16 (T-2062) .. 5-389

5-509 Differential Pressure, DP-0760: Test No. 16 (T-2062) ... 5-390

5-510 Integrated SGRR Flow: Test No. 16 (T-2062) 5-390

5-511 Primary System (Pressurizer) Pressure (P-139): Test No. 16 (T-2063) 5-391

LIST OF FIGURES (Continued)

Figure Page

5-512 Primary Fluid T_{hot} (T-1150): Test No. 16 (T-2063) 5-391

5-513 Primary Fluid Flow Rate (WF-109): Test No. 16 (T-2063) . 5-392

5-514 Secondary Side Pressure (P-7): Test No. 16 (T-2063) 5-392

5-515 Downcomer Water Level - Wide Range (WL-9321): Test No. 16 (T-2063) 5-393

5-516 SGTR Flow Rate (WF-150): Test No. 16 (T-2063) 5-393

5-517 SORV Flow Rate (WF-01): Test No. 16 (T-2063) 5-394

5-518 SORV Tank Level (LT-3): Test No. 16 (T-2063) 5-394

5-519 Secondary Fluid Temperature (STC-34): Test No. 16 (T-2063) 5-395

5-520 Secondary Fluid Temperature (STC-55): Test No. 16 (T-2063) 5-395

5-521 Secondary Fluid Temperature (STC-60): Test No. 16 (T-2063) 5-396

5-522 Secondary Fluid Temperature (STC-61): Test No. 16 (T-2063) 5-396

5-523 Differential Pressure, DP-0404A: Test No. 16 (T-2063) .. 5-397

5-524 Differential Pressure, DP-0808A: Test No. 16 (T-2063) .. 5-397

5-525 Differential Pressure, DP-0760: Test No. 16 (T-2063) ... 5-398

5-526 Integrated SGTR Flow: Test No. 16 (T-2063) 5-398

5-527 Primary System (Pressurizer) Pressure (P-139): Test No. 16 (T-2064) 5-399

5-528 Primary Fluid T_{hot} (T-1150): Test No. 16 (T-2064) 5-399

5-529 Primary Fluid Flow Rate (WF-109): Test No. 16 (T-2064) . 5-400

5-530 Secondary Side Pressure (P-7): Test No. 16 (T-2064) 5-400

5-531 Downcomer Water Level - Wide Range (WL-9321): Test No. 16 (T-2064) 5-401

LIST OF FIGURES (Continued)

Figure Page

5-532 SGTR Flow Rate (WF-150): Test No. 16 (T-2064) 5-401

5-533 SORV Flow Rate (WF-01): Test No. 16 (T-2062) 5-402

5-534 SORV Tank Level (LT-3): Test No. 16 (T-2064) 5-402

5-535 Secondary Fluid Temperature (STC-34): Test No. 16 (T-2064) 5-403

5-536 Secondary Fluid Temperature (STC-55): Test No. 16 (T-2064) 5-403

5-537 Secondary Fluid Temperature (STC-60): Test No. 16 (T-2064) 5-404

5-538 Secondary Fluid Temperature (STC-61): Test No. 16 (T-2064) 5-404

5-539 Differential Pressure, DP-0404A: Test No. 16 (T-2064) .. 5-405

5-540 Differential Pressure, DP-0808A: Test No. 16 (T-2064) .. 5-405

5-541 Differential Pressure, DP-0760: Test No. 16 (T-2064) ... 5-406

5-542 Integrated SGTR Flow: Test No. 16 (T-2064) 5-406

5-543 Primary System (Pressurizer) Pressure (P-139): Test No. 16 (T-2065) 5-407

5-544 Primary Fluid T_{hot} (T-1150): Test No. 16 (T-2065) 5-407

5-545 Primary Fluid Flow Rate (WF-109): Test No. 16 (T-2065) .. 5-408

5-546 Secondary Side Pressure (P-7): Test No. 16 (T-2065) 5-408

5-547 Downcomer Water Level - Narrow Range (WL-9360): Test No. 16 (T-2065) 5-409

5-548 Downcomer Water Level - Wide Range (WL-9321): Test No. 16 (T-2065) 5-409

5-549 SORV Flow Rate (WF-01): Test No. 16 (T-2065) 5-410

5-550 SORV Tank Level (LT-3): Test No. 16 (T-2065) 5-410

5-551 SGTR Flow Rate (WF-150): Test No. 16 (T-2065) 5-411

LIST OF FIGURES (Continued)

Figure Page

5-552 Differential Pressure, DP-0404A: Test No. 16 (T-2065) .. 5-411

5-553 Differential Pressure, DP-0808A: Test No. 16 (T-2065) .. 5-412

5-554 Differential Pressure, DP-0760: Test No. 16 (T-2065) ... 5-412

5-555 Secondary Fluid Temperature (STC-34): Test No. 16 (T-2065) 5-413

5-556 Secondary Fluid Temperature (STC-55): Test No. 16 (T-2065) 5-413

5-557 Secondary Fluid Temperature (STC-60): Test No. 16 (T-2065) 5-414

5-558 Secondary Fluid Temperature (STC-61): Test No. 16 (T-2065) 5-414

5-559 Integrated SGTR Flow: Test No. 16 (T-2065) 5-415

5-560 Variation in Tracer Concentrations: Blowdown Phase, Test No. 16 (T-2061) 5-416

5-561 Comparison Between S-1 (○) and IKP-4 (▲) Results After Correction for Sample Line Delays: Blowdown Phase Test No. 16 (T-2061) 5-417

5-562 Variation in Tracer Concentrations: SGTRs at 60 and 105 in., Test No. 16 (T-2062 and T-2063) 5-418

5-563 Comparison Between S-1 (○) and IKP-4 (▲) Results After Correcting for Sample Line Delays: SGTRs at 60 and 105 in., Test No. 16 (T-2062 and T-2063) 5-419

5-564 Variation in Tracer Concentrations: SGTRs at 155 and 285 in., Test No. 16 (T-2064 and T-2065) 5-420

5-565 Comparison Between S-1 (○) and IKP-4 (▲) Results After Correcting for Sample Line Delays: SGTRs at 155 and 285 in., Test No. 16 (T-2064 and T-2065) 5-421

5-566 Variation in SORV Tracer Concentrations After Correcting for Sample Line Delays: Test No. 16 (T-2061 and T-2065) 5-422

6.1 Measured and Calculated Masses in MB-2: Tests (T-2055 to T-2059) 6-6

LIST OF FIGURES (Continued)

Figure		Page
6.2	Density Distribution in MB-2. Initial Downcomer Level: 62 in. Test T-2055	6-7
6.3	Density Distribution in MB-2. Initial Downcomer Level: 104 in. Test T-2056	6-8
6.4	Density Distribution in MB-2. Initial Downcomer Level: 152.5 in. Test T-2057	6-9
6.5	Density Distribution in MB-2. Initial Downcomer Level: 285 in. Test T-2058	6-10
6.6	Density Distribution in MB-2. Initial Downcomer Level: 440 in. Test T-2059	6-11
7.1	Test Transient for 10% SORV Flow with SGTR and Loss of Off-site Power, (Test No. 12) Showing Conditions for Steady-State Tests	7-51
8.1	Measured and Predicted Voidage with Respect to Height in Model Boiler	8-34

BEST COPY AVAILABLE

LIST OF TABLES

Table **Page**

2.1 Downcomer Volume/area Comparison 2-17

2.2 Test Loop Equipment Specifications 2-18

3.1 Location of MB-2 Tube Bundle Pressure Taps 3-4

3.2 Tube Bundle Differential Pressure Measurements 3-4

3.3 Location of Pressure Taps in MB-2 Lower Downcomer Region 3-6

3.4 Lower Downcomer Region Differential Pressure Measurements 3-6

3.5 Downcomer Pipe Fluid Thermocouples (DTCs) 3-8

3.6 "Dead Space" Fluid Thermocouples (DTCs) 3-8

3.7 Wrapper Box Wall Thermocouples (WTCs) 3-8

3.8 Location of Pressure Taps in MB-2 Upper Shell Region 3-10

3.9 Location of Upper Downcomer Thermocouples 3-11

4.1 Precision of Analyses for Lithium and Potassium 4-7

5.1 Analytical Results, Test 1 (T-1952) 5-63

5.2 Sample Line Flow Rates, Test 1 (T-1952) 5-64

5.3 Analytical Results, Test 2 (T-1958) 5-65

5.4 Sample Line Flow Rates, Test 2 (T-1958) 5-66

5.5 Analytical Results, Test 3 (T-1970) 5-67

5.6 Sample Line Flow Rates, Test 3 (T-1970) 5-68

5.7 Analytical Results, Test 4 (T-1982) 5-69

5.8 Sample Line Flow Rates, Test 4 (T-1982) 5-70

5.9 Analytical Results, Test 5 (T-1972) 5-71

5.10 Sample Line Flow Rates, Test 5 (T-1972) 5-72

5.11 Analytical Results, Test 6 (T-1957) 5-73

LIST OF TABLES (Continued)

Table		Page
5.12	Sample Line Flow Rates, Test 6 (T-1957)	5-74
5.13	Analytical Results, Test 7 (T-1966)	5-75
5.14	Sample Line Flow Rates, Test 7 (T-1966)	5-76
5.15	Analytical Results, Test 8 (T-1975 to T-1979)	5-77
5.16	Sample Line Flow Rates, Test 8 (T-1975 to T-1979)	5-79
5.17	Analytical Results, Test 9 (T-1988 to 1992)	5-80
5.18	Sample Line Flow Rates, Test 9 (T-1988 to T-1992)	5-82
5.19	Analytical Results, Test 10 (T-1998)	5-83
5.20	Sample Line Flow Rates, Test 10 (T-1998)	5-85
5.21	Analytical Results, Test 11 (T-2003)	5-86
5.22	Sample Line Flow Rates, Test 11 (T-2003)	5-89
5.23	Analytical Results, Test 12 (T-2001)	5-90
5.24	Sample Line Flow Rates, Test 12 (T-2001)	5-92
5.25	Analytical Results, Test 13 (T-2069)	5-93
5.26	Sample Line Flow Rates, Test 13 (T-2069)	5-94
5.27	Analytical Results, Test 14 (T-2067)	5-95
5.28	Sample Line Flow Rates, Test 14 (T-2067)	5-96
5.29	Analytical Results, Test 15 (T-2050 to T-2054)	5-97
5.30	Sample Line Flow Rates, Test 15 (T-2050 to T-2054)	5-99
5.31	Analytical Results, Test 16 (T-2061 to T-2065)	5-100
5.32	Sample Line Flow Rates, Test 16 (T-2061 to T-2065)	5-102
6.1	Actual Initial Conditions of Mass Blowdown Tests	6-4
6.2	Measured and Calculated Masses in MB-2	6-5
7.1	Predicted Contribution of Volatility to Observed Carryover	7-33

LIST OF TABLES

Table Page

7.2 Comparison of Observed and Calculated Conductivities 7-34

7.3 Masses of Lithium and Potassium added to MB-2 7-36

7.4 Estimates of MB-2 Liquid Mass at Normal or High Water Level 7-37

7.5 Calculated Concentrations for Test 2 (T-1958) 7-38

7.6 Calculated Concentrations and Lithium Masses for Low Level Tests With Recirculation 7-39

7.7 Calculated and Measured Ratios of Tracer Chemicals for Low Level Tests Without Recirculation 7-41

7.8 Calculated Concentrations for Test 14 (T-2067) 7-42

7.9 Steady-State Carryover at Normal or High Water Level 7-43

7.10 Upper Limits for Steady-State Primary Coolant Bypassing at Normal or High Water Level 7-44

7.11 Transient Releases at Normal or High Water Level 7-45

7.12 Comparison of Tracer Concentrations in SORV Condensate and in Model Boiler Water During the Pressure Relief Cycles of Test 11 (T-2003) 7-46

7.13 Steady-State Carryover at Low Water Level 7-47

7.14 Upper Limits for Steady-State Primary Coolant Bypassing at Low Water Level 7-48

7.15 Transient Releases at Very Low Water Level 7-49

7.16 Transient Releases at Intermediate Water Level 7-50

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XLIV

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SECTION 1

INTRODUCTION

In normal operation, PWR steam generator tubing can be damaged by a variety of corrosion or mechanical wear processes. If this damage causes a tube leak and if steam is vented to atmosphere, a pathway exists for the direct release of radioactive fission products to the environment. This possibility has long been recognized to the extent that a full double-ended guillotine break of a single steam generator tube is considered as a design basis fault by the USNRC and by regulatory bodies elsewhere. Currently, for these faults, activity levels in the primary circuit are set at a value such that even a full break will not give an activity release which exceeds that laid down in 10 CFR Part 100 (1). None of the seven steam generator tube rupture (SGTR) events that have occurred has exceeded this limit (2, 3).

In any SGTR fault the amount of activity released will depend on the degree of active species retention in the steam generator, as well as on the activity levels in the primary coolant. For primary coolant that has mixed fully with the bulk steam generator, the retention is assumed to be similar to that which exists under normal operating conditions (4). Thus, it is assumed that there is no retention of noble gases, 1% carryover by mass of iodine with the steam, and 0.1% carryover by mass of cesium (and similar non-volatile fission products). In this code the carryover of cesium was derived directly from measured levels of moisture carryover, while that for iodine was based on steam volatility.

In addition to the release of fission products from the bulk steam generator water, there exists the possibility that some primary coolant may be released without having first mixed with the bulk water (a process defined here as primary coolant bypassing). Here it is postulated that the primary coolant will flash as it leaves the tube break and in so doing it will form very fine droplets which may be carried in steam bubbles through the bulk water to the separators. A fraction of these droplets may be small enough to pass through the separators to be released to the atmosphere (5, 6 and 7). Such uncertainties can not be quantified because of lack of experimental data and

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as a consequence the U.K. safety case for the Sizewell B PWR has made the conservative assumption that no retention will occur in SGTR faults involving releases to the environment.

The assumptions made in the current assessment routes can only be confirmed by experimental measurements on plant or under prototypical conditions. More importantly, the assessment routes can only be improved if experimental data are available and if the processes which govern the release of active species are understood. As part of a cooperative USNRC, EPRI and Westinghouse program to provide these data, programs are in hand to quantify iodine volatility under steam generator fault conditions and to define levels of carryover and bypassing (8). The MB-2 Phase II Test Program forms part of this overall program and was specifically designed to quantify levels of carryover and bypassing in SGTR/SORV (coincident steam generator tube rupture and stuck-open safety relief valve) faults and in SGTR overfill faults. For this phase of the test program funding was provided jointly by USNRC, EPRI, Westinghouse and by the U.K. Central Electricity Generating Board. It is anticipated that the data provided by these programs will have a significant impact on the design and on the operational and inspection requirements needed to meet regulatory requirements for activity release. In particular, they may determine the importance placed on maintaining very low primary coolant activity levels, the economic consequences for fuel integrity, the assumed frequencies of SGTR and SORV events and, finally, the costs and operational exposure incurred in maintenance and inspection if either the SGTR frequency (unresolved issues A-3, A-4 and A-5 (9)) or SORV frequency needs to be reduced.

1-1. TEST MATRIX

The original matrix proposed is shown in Table 1-1 and consisted of six steady-state and three transient tests. The test conditions selected for the steady-state tests correspond to three instants of time in a complete SGTR/SORV transient at which the dominant fission product release mechanisms could change. These times are 900 seconds (Tests 2.3, 2.4, and 2.5), 4000 seconds (Test 2.2) and 15000 seconds (Test 2.1).

In Test 2.1, because of the small degree of superheat and low SGTR discharge velocity, the preferential release of primary coolant (primary coolant bypassing) was not expected and it was believed that the primary coolant would mix with the bulk liquid. In Tests 2.2 to 2.5 primary coolant bypassing was considered possible, either because of flashing or the higher velocity of the SGTR discharge. In one test, Test 2.5, the dryer was to be bypassed to assess its effect on carryover.

Tests 2.7 and 2.9 were designed to simulate SGTR/SORV transients with the SGTR occurring at the bottom or top of the tube bundle, respectively, and when offsite power was not available. In both transients the auxiliary flow was to be maintained to t = 15000 seconds at a rate sufficient to maintain normal water level. This procedure was adopted as it was believed that the mechanisms for fission product retention would be significantly different if the steam generator were to dry out completely or if a significant fraction of the surface area of the tube bundle were to dry out. There are several reasons for the belief. Fission products could be deposited as solids on dry surfaces and possibly react with the surface oxides. This could result in enhanced retention. However, if any reaction leads to the formation of volatile species, the fission product release could be enhanced. Alternatively, if the SGTR break flow sprays onto a region of dry surface, boiling may involve concentration of the fission product and lead to enhanced release either by an increase in volatility or by the release of droplets containing more concentrated solutions of primary coolant.

Test 2.8 was designed to simulate a top break SGTR transient in which the steam generator overfills and where the pressure is relieved by repeated cycling of the safety relief valve. This test was based on the SGTR at the R. E. Ginna plant (2), when continued operation of the charging pumps to maintain primary circuit pressure, and with the faulted steam generator isolated, caused both the level and steam generator pressure to rise.

The initial phase of this test matrix was carried out over the period 3/14/85 to 3/27/85. This consisted of Test 2.3 (T-1952), Test 2.2 (T-1970) and Test

2.1 (T-1972). These were supplemented by a group of diagnostic tests to quantify moisture carryover in the absence of an SGTR and an SGTR at reduced water level. These tests were a moisture carryover test at 8% power (T-1957, at conditions corresponding to Test 2.3), a moisture carryover test at 100% power (T-1966), and a top break SGTR test with an 8% SORV steam flow rate and at reduced water level (T-1958, also under Test 2.3 conditions.) To simplify reporting, these tests have been reordered and renumbered as part of the revised test matrix shown in Table 1-2.

As the initial series of six tests gave very low carryover, the test matrix was revised to cover test conditions that might promote higher levels of carryover. Principally, the revision involved the deletion of Test 2.7, a revised version of Test 2.2, designed to promote flashing of the primary coolant as it emerges from the SGTR break (T-1982), and the inclusion of two tests, revised versions of Tests 2.3 and 2.4, designed to examine the carryover at very low water levels. These latter tests were split into five sections, blowdown to a water level of 50 in. followed by four successive SGTR phases at progressively higher water levels. Finally, because it was important to define the contribution of the dryer in obtaining the low observed carryover, Test 2.5 was deleted and replaced by four tests in which the dryer was bypassed. These tests were repeats of the modified versions of Tests 2.2, 2.3 and 2.4 and a further 100% power moisture carryover test. In all these tests the SORV steam flow rate was increased to 10% and, generally, the primary coolant temperature increased to promote flashing. The revised test matrix is given in Table 1-2; again, to simplify reporting, all tests have been reordered and renumbered.

The final test in the original test matrix, Test 2.6, was a scoping trial designed to provide information on fission product retention when both the primary circuit and steam generator have dried out completely. Under these severe accident conditions the postulated route for fission product release is an aerosol originating from the molten reactor core. This test was carried out as a separate test program immediately before the MB-2 unit was modified to bypass the dryer. The results for this group of tests are given in Appendix 1.

1-2. TESTING METHODOLOGY

In the test program the SORV was represented in MB-2 by a steam line break (SLB), of equivalent area, and the assumption was made that the water carried over into the MB-2 steam line is representative of that which would be released to the atmosphere via an SORV in a Model F steam generator. To simulate the cases where either all four or only one steam generator contribute to the SORV steam flow, two SORV lines were provided. These were scaled to give either 2% or 8% of the steam flow at 100% power.

To simulate the SGTR, two break lines were fitted to the model boiler. Of these, one was located above the tube bundle with the break location positioned such that the jet of primary coolant would be directed upwards towards the primary separator The second line entered the tube bundle just above the tube sheet. While the latter location is more representative of most modes of tube failure, the former location would be expected to maximize any primary coolant bypassing.

In each test, different chemical tracers were used in the primary loop (potassium) and in the model boiler (lithium), so that it would be possible to distinguish between moisture carryover from the bulk steam generator water or that due to primary coolant bypassing. These species were monitored by taking continuous samples of the primary loop, the model boiler and the SORV condensate, and by analyzing for the two different tracers by atomic emission spectrophotometry.

A detailed description of the MB-2 test facility and its instrumentation is given in Sections 2 and 3, a description of the chemical control and instrumentation in Section 4, details of the individual tests in Section 5 and the analysis of the results in Sections 6 and 7. The overall conclusions of the test program are given in Section 8.

1-3. REFERENCES

1. Code of Federal Regulations, Title 10, Part 100, Reactor Site Criteria

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3. NRC Report on the January 25, 1982 Steam Generator Tube Rupture at R. E. Ginna Nuclear Power Plant, NUREG 0909 (1982).

4. Calculation of Releases of Radioactive Materials in Gaseous and Liquid Effluents from Pressurized Water Reactors, NUREG 0017 (1976).

5. A. K. Postma and P. S. Tam, Iodine Behavior in a PWR Cooling System Following a Postulated Steam Generator Tube Rupture Accident, NUREG-0409 (1978).

6. A. K. Postma, G. M. Hesson and D. W. Falette, Iodine Transport Predicted for a Postulated Steam Line Break With Concurrent Ruptures of Steam Generator Tubes, NUREG/CR 2659, PNL-3794 (1983).

7. S. Raghuram, P. Baybutt, R. S. Denning and H. Jordan, Iodine Behavior in Steam Generator Tube Rupture Accidents, NUREG/CR-2683, BMI-2094 (1982).

8. J. Hopenfeld, Experience and Modeling of Radioactivity Transport Following Steam Generator Tube Rupture, Nuclear Safety, 26, p. 286 (1985).

9. NRC Integrated Program for the Resolution of Unresolved Safety Issues A-3, A-4 and A-5 Regarding Steam Generator Tube Integrity, Draft Report for Comment, NUREG-0844 (1986).

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TABLE 1-1

PHASE II TEST MATRIX

Test Type***	Primary* P_1 (psia), T_1 (°F)	Secondary* P_2 (psia)	Comments
2.1 Steady-state with SORV** bottom break	170, 320	85	To assess low velocity discharge without flashing.
2.2 Steady-state with SORV bottom break	557, 427	287	To assess flashing break flow.
2.3 Steady-state with SORV bottom break	1850, 560	1080	To assess high velocity discharge without flashing.
2.4 Steady-state with SORV top break	1850, 560	1080	To assess effect of break location.
2.5 Steady-state with primary top break, no dryer	1850, 560	1080	To determine effect of dryer on carryover. Upper shell must be removed.
2.6 Steady-state with primary superheat with non-condensible	- -	-	Test conditions to be defined by EPRI.
2.7 Transient SGTR & SORV with bottom break	Primary conditions taken from analytical calculations simulating PWR response to SGTR + SORV		Auxiliary feed remains on until 15,000 s, then stopped and SG allowed to boil dry.
2.8 Overfill transient with top break	Primary conditions held constant		Overfill simulated with normal safety valve operation, followed by SORV, no SGTR.
2.9 Transient SGTR & SORV with top break	Same as test 2.7		Test 2.9 to be performed as a continuation of test 2.4, with boundary conditions as close as possible to those for test 2.7.

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* Preliminary conditions - parameters to be confirmed following thermal-hydraulic support analysis.

** SORV - Stuck-Open Safety Valve

*** Tests are preceded by steady-state measurements without SGTR

TABLE 1-2

REVISED PHASE II TEST MATRIX

Test Number	Test Type	Test Reference Number	Primary P_1 (psia),	T_1 (°F)	Secondary P_2 (psia)	Comments
1	2.3 Steady-state 2% SORV - bottom break	T-1952	1850	560	1080	Shakedown test
2	Steady-state 8% SORV - top break	T-1958	1850	574	1015	Investigation of low S/G water
3	2.2 Steady-state 8% SORV - bottom break	T-1970	557	427	287	
4	2.2 Steady-state Revised 10% SORV - bottom break	T-1982	557	470	305	Test 5 revised to increase of SGTR flow and to promote flashing.
5	2.1 Steady-state 8% SORV - bottom break	T-1972	170	320	85	To assess low velocity discharge without flashing
6	8% power moisture carryover	T-1957	1842	580	1000	8% SORV flow
7	100% power moisture carryover	T-1966	2215	617	1015	Variable S/G water level

TABLE 1-2 (Continued)

REVISED PHASE II TEST MATRIX

Test Number	Test Type	Test Reference Number	Primary P_1 (psia),	T_1 (°F)	Secondary P_2 (psia)	Comments
8	2.4 Steady-state 10% SORV-top break. Revised test with blowdown to 50 in. water level followed by SGTRs at levels of about 60, 100, 150 and 280 ins.	T-1975 to T-1979	1850	580	1080	SORV was increased from 8% to 10%: T_1 was increased from 560°F to 580°F; original test only at normal water level.
9	2.3 Steady-state 100% SORV - bottom break. Revised test as in Test 8	T-1988 to T-1992	1850	580	1080	SORV was increased from 8% to 10%: T_1 was increased from 560°F to 580°F; original test only at normal water level.
10 and 11	2.8 Overfill transient - top break	T-1998 and T-2003	1850	580	1000	T_1 was increased from 560°F to 580°F; max. SORV was increased from 8% to 10%. Test 11 used an improved method of SORV sampling.
12	2.9 Full transient, 2% to 10% SORV - top break	T-2001	Primary conditions taken from analytical calculations simulating PWR response to SGTR + SORV.			SORV was increased from 8% to 10%.

9

TABLE 1-2 (Continued)

REVISED PHASE II TEST MATRIX

Test Number	Test Type	Test Reference Number	Primary P_1 (psia),	T_1 (°F)	Secondary P_2 (psia)	Comments
13	100% power with dryer bypassed	T-2069	2250	615	1015	Repeat of Test 7 with dryer bypassed
14	2.2 Steady-state 10% SORV - bottom break, dryers bypassed	T-2067	577	470	305	Repeat of Test 5 with dryer bypassed
15	2.4 Steady-state 10% SORV - top break, dryers bypassed.	T-2050 to T-2054	1850	580	1080	Repeat of Test 8 with dryer bypassed
16	2.3 Steady-state 10% SORV - bottom break, dryers bypassed	T-2061 to T-2065	1850	580	1080	Repeat of Test 9 with dryer bypassed
17	2.6 Aerosol tests with 1-2 and 35 micron particles					See Appendix 1

SECTION 2

THE MB-2 TEST FACILITY

2-1. DESCRIPTION OF MODEL BOILER

The Model Boiler No. 2 (MB-2) is an approximately 0.8-percent power-scaled model of the Model F steam generator, a feedring type unit. It is designed to be geometrically and thermal-hydraulically similar to the Model F in important areas and it is capable of generating a maximum of 10 MWt. At 100-percent power (6.67 MWt) it produces dry, saturated steam at 6.9 Mpa (1000 psia), the same as in the Model F. A schematic of the model as configured for the Phase II tests is shown in Figure 2-1, while a typical Model F steam generator is shown in Figure 2-2.

Within the model, dry saturated steam is generated by the transfer of heat from primary side high pressure water at 15.5 Mpa (2250 psia) to a steam and water mixture on the secondary side. The primary water enters the inlet side of the channel head, flows through the U-tubes, and leaves through the exit side of the channel head.

On the secondary side, feedwater or auxiliary feedwater enters the "unit cell" surrounding the primary separator where it mixes with the recirculating water. The latter flows down the downcomer pipes, and then enters the tube bundle through the wrapper box cutouts which lie just above the tubesheet. The flow is directed across the tubesheet by a flow distribution baffle before the flow turns upwards to pass through the tube bundle. As the fluid travels upward, a steam-water mixture is generated. When this mixture leaves the top of the tube bundle, it flows through a cone into the riser, at the top of which is the primary separator. The latter removes the water by centrifugal action and returns it to the downcomer circuit. The steam, with entrained moisture, then enters the secondary separator (dryer) where the moisture is removed by a single-tier vane type separator and is returned to the downcomer circuit via a straight drain pipe (Figure 2-1). The steam, exiting the vessel through the outlet nozzle, is saturated and essentially dry.

2-1-1. Tube Bundle

The MB-2 tube bundle is composed of 52 tubes arranged in a rectangular array having 13 tube rows and 4 tube columns, as shown in Figure 2-3. All tubes are fabricated from Inconel 600. They have the same outside diameter (1.75 cm, 11/16 in.) and wall thickness (1 mm, 0.040 in.) as the tubes in the Model F and are configured in the same 2.49 cm (0.98 in.) square-pitch array. As a result, the primary and secondary unit cell flow areas for the model and the full-size steam generator are identical. The straight length of the tube bundle is 6.69 meters (21.94 ft.), which is about 0.5 meter (20 in.) shorter than in the Model F. The radii of the U-bends and the length of the tubes are as defined in Figure 2-4.

There are six tube supports in the MB-2 bundle, compared with seven supports in the Model F, and also a flow distribution baffle (Figure 2-1). The tube support plates utilized in MB-2 provide a full-size simulation of the tube/support plate juncture in a representative environment. The plates, with the exception of the grid at the third support location, have the same thickness and make use of the same quatrefoil broached hole configuration as is used in the full-size Model F. The support plates in MB-2 are partially composed of alternate broached (40) and drilled hole (12) designs. The axial spacing of the tube supports was selected to be identical to that which exists in the Model F, 1.02 m, (40.16 in.). The flow distribution baffle is located 0.5 meter (20 in.) above the top of the tubesheet, as in the Model F. It is partially configured with oversized drilled holes and an alternate "mini-broached" quatrefoil hole design. The baffle also includes a central cutout which simulates the effect of the central cutout in the Model F.

The heat transfer area of the MB-2 tube bundle is 39.75 m^2 (428 $ft.^2$). Utilizing this area, a scaling philosophy was adopted which maintains the same bundle average heat flux as exists in the Model F. This power scaling was subsequently used in sizing the flow areas for the downcomers and the primary and secondary separators to provide velocities and mass fluxes which are comparable to those of the Model F. This scaling approach, as it applies to transient testing, is described in more detail in reference 1 (Section 2-3).

12

2-1-2. MB-2 Upper Shell Region

Figure 2-5 is a schematic of the upper shell region. A cross-sectional view at the deckplate is shown in Figure 2-6. Detailed descriptions of the components are provided in the following sections.

Modular Primary Separator -- The MB-2 modular separator employs four swirl vane blades oriented at 37° from the horizontal, the same as specified in some existing designs. The hub of the swirl vane is slightly elongated and is more streamlined than earlier units. The major design change, in addition to the overall size reduction, is that the riser downstream of the hub is perforated with 0.8 cm (0.31 in.) diameter holes, evenly spaced around the circumference. These holes allow the liquid, which has been forced to the periphery of the riser pipe by the centrifugal motion imparted by the blades, to exit the riser and enter the annulus formed by the riser and the riser barrel. The remaining steam/liquid mixture continues to flow upwards into the orifice, which also strips off some portion of the liquid. Figure 2-7 provides a schematic of the steam and liquid flow paths in the upper shell region. The riser barrel extends down approximately 48 cm (19 in.) below the deck plate. Both the riser and riser barrel cylinders are concentrically located about the center of the MB-2 shell (Figure 2-6).

Outside of the riser barrel, the unit cell cylinder serves to define the local cross-sectional area which is associated with a single modular separator in a full-size steam generator. A unit cell partition is necessary because the cross-sectional area enclosed within the MB-2 shell is much too large for a single modular separator. The unit cell also encloses the appropriate areas for liquid drainage and steam venting through the deck plate. Liquid which collects on the deck plate is removed by drain pipes which extend from the deck plate down to the intermediate deck plate. The vent area is represented by a pipe which extends 12.7 cm (5 in.) above the deck plate. The extension is provided to minimize the potential for reentrainment of any liquid which may be present on the deck plate. Additional vent area is also provided within the unit cell to represent a portion of the steam vent area present in the annular space between the deck plate and shell in the full-size steam

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generator. The edge of the deck plate is ringed with a 10 cm (4 in.) dam that limits the possibility of liquid reentrainment in the steam vented through the deck plate-to-downcomer drum gap. The sizing and layout of these various components are discussed in more detail in the following paragraph.

The riser and riser barrel cylinders used in the MB-2 are identical to those of the prototype modular separator, along with the swirl vane, hub, and orifice. The selection of the appropriate cross-sectional areas within the unit cell, downcomer drum, liquid drain and steam vents was based on matching the areas present in a typical modular separator configured in a Model F shell. Figure 2-8 provides a schematic of a Model F upper shell region configured with 130 modular separators. The separators are arranged in a 26 cm (10.25 in.) square pitch array. The specific arrangement of separators is constrained by the available space enclosed by the feedwater distribution ring. Within the array there are 90 interstitial deck drains and 25 deck vents. In addition, there is a larger cylindrical drain in the center of the array. In the annular space between the edge of the deck plate and the shell there is approximately 4.5 m^2 (48 $ft.^2$) of area also available for steam venting. This annular area is more accessible to the modular separators located on the periphery of the array. Separators positioned in the interior of the array would not be influenced by this free space. Hence, a variety of separator situations exist from the outside to the inside of the array. It was decided to assign one-half of this peripheral area (on a per separator basis) to the region which lies within the unit cell for use in defining an average or typical modular separator configuration for the MB-2. This portion is therefore more local to the operation of the separator. The remaining one-half of the peripheral area will be contained within the downcomer drum, which, in effect, serves as a new shell for the single modular separator assembly. The following calculations summarize the derivation of the various areas in the Model F primary separator region and the corresponding areas specified for the MB-2:

14

Model F

- Total area within shell = 14.39 m^2 (154.9 $ft.^2$)
- Number of modular separators = 130
- Shell area for each separator = 0.111 m^2 (1.19 $ft.^2$)
- Total annular area between edge of deck plate and shell = 4.47 m^2 (48.1 $ft.^2$)
- Portion of total annular area to assign to each separator = 0.34 m^2 (0.37 $ft.^2$)
- Number of deck drains (3.5 inch Sch. 40 pipes, 9.89 in^2 inside) = 90
- 1 central drain: area = 0.045 m^2 (0.49 $ft.^2$)
- Total deck drain area = 0.62 m^2 (6.7 $ft.^2$)
- Deck drain area for each separator = 0.0047 m^2 (0.051 $ft.^2$)
- Number of deck vents (3.5 inch Sch. 40 pipes, 9.89 in^2 inside) = 25
- Total deck vent area = 0.16 m^2 (1.71 $ft.^2$)
- Deck vent area for each separator = 0.00123m^2 (0.0132 $ft.^2$)

MB-2

desired
[Model F value]

- Downcomer drum: outer diameter = 40 cm (15.75 in.)
  inner diameter = 38.7 cm (15.25 in.)

- Unit cell: outer diameter = 34.9 cm (13.75 in.)
  inner diameter = 33.6 cm (13.25 in.)

- Area enclosed within downcomer drum (excluding unit cell piping metal) = 1110 cm^2 (172.1 in.^{2}) [1106 cm^2 (171.5 in.^{2})]

- Area enclosed within unit cell = 890 cm^2 (137.9 in.^{2}) [935 cm^2 (144.9 in.^{2})]

- Deck drain area (2 and 2 1/2 inch Sch. 40 pipes) = 52.9 cm^2 (8.2 in.^{2}) [47.4 cm^2 (7.4 in.^{2})]

- Deck vent area (1 1/2 inch Sch. 40 pipe) = 13.2 cm^2 (2.04 in.^{2}) [12.26 cm^2 (1.9 in.^{2})]

- Additional vent area included within unit cell to account for 1/2 peripheral vent area assigned to a typical modular separator $\simeq$ 176.8 cm^2 (27.4 in.^{2}) [171.6 cm^2 (26.6 in.^{2})]

The small differences between the desired areas and the actual MB-2 areas are primarily due to the use of commercially available pipes for the various components.

Downcomer -- As discussed previously, a cylindrical downcomer drum, 38.7 cm (15.25 in.) in diameter, is used to limit the upper downcomer cross-sectional area to a value which corresponds to the area associated with a single modular separator configured in a Model F steam generator. The lower downcomer volume therefore only includes the water contained within the two 7.8 cm (3.07 in.) ID pipes that feed into the hot and cold leg wrapper openings to the bundle. These pipes were scaled to represent the cross-sectional area in the Model F lower downcomer annulus.

A funnel was needed to link the upper cylindrical drum to the lower downcomer pipes (Figure 2-5). The design specified for the funnel is such that the enclosed water volume is minimized, again to simulate better the Model F downcomer response. The drainage from the secondary separator is channeled into the downcomer funnel via a straight pipe of scaled size, as shown in Figure 2-5.

Table 2-1 provides a comparison of the downcomer cross-sectional areas and component volumes in MB-2 and Model F. The differences between desired and actual values are a result of use of commercially available material.

Feedwater Inlet -- For the Phase II tests the main feedwater penetration and distribution was at the 993 cm (391 in.) elevation. The auxiliary feedwater line penetrated the shell at 1016 cm (400 in.) and discharged at 1018 cm (401 in.).

Structural Protection -- The downcomer drum, dryer shroud and tube bundle wrapper box are reinforced with stiffener plates to allow for a maximum differential pressure of 140 psid across these walls. To provide steam to the dead space between the test model and the shell and thus to equalize the pressures in the model and the dead space during startup and normal operation, a 1/2-inch check valve (with cracking pressure = 6 ± 2 psid) was installed in the deck plate supporting the dryer (Figure 2-9). Also, two 2-inch check valves were installed in the deck plate to prevent collapse of the test section, and two 2-inch check valves were installed to prevent rupture of the test section during blowdown. (The 2-inch check valves had a cracking pressure of 90 ± 6 psid). To depressurize the dead space at essentially the same rate as test section is depressurized, a 4-inch control valve was installed into a blowdown line connected to the dead space. This valve is controlled from the signal of a differential pressure transducer connected between the test section and the dead space.

2-2. TEST LOOP DESCRIPTION

2-2-1. General Description

The test facility associated with MB-2 is a pressurized water heat supply loop and a steam cycle complex constructed primarily for the thermal-hydraulic testing of model steam generators. The test facility can also be used for flow tests of components or for materials tests on prototype parts in a high-purity water chemistry environment, where the carbon steel piping materials are not adversely affected by corrosion.

The high pressure-high temperature MB-2 test facility complex consists of three main systems, primary, secondary, and tertiary, with the attendant process instrumentation and control systems. The following paragraphs describe the three systems and the modifications that were required to the primary and secondary loop to accomplish the various tests of the MB-2 Transient Test Program.

2-2-2. Primary Loop

The primary or heat supply system is a closed pressurized water loop, consisting of a pump, a flow control valve, a 10 MW natural-gas-fired heater as the primary heat source, two 3.5 MW gas-fired heaters, used for isothermal or low power operation, a pressurizer, and a model steam generator (MB-2) as the heat sink. The test loop has a design pressure of 17.22 Mpa (2500 psia) and a design temperature of 344°C (650°F). Numerous temperatures, pressures, and flow rates are monitored to provide safe operation of equipment and for data collection purposes. A schematic of the primary loop flow paths is shown in Figure 2-10, and the main equipment specifications are given in Table 2-2.

Primary Loop Makeup System -- The primary loop was modified for the Phase II test program by the installation of a 1500 gallon primary makeup tank and its associated chemical dosing pipework. This modification ensured that any primary water lost via the simulated tube rupture could be replaced by dosed makeup water of a similar chemical composition, hence avoiding major changes in composition during the transient tests.

19

The primary makeup system consisted of two positive displacement charging pumps, a low capacity (4 GPM) variable speed unit and a high capacity (8 GPM) single speed unit, which drew water from either the makeup tank or a demineralized water supply. During startup, shutdown or normal operation, the primary makeup water was drawn from the demineralized water supply. The makeup tank water chemistry was matched with the primary loop chemistry prior to a tube rupture test and the charging pumps suction switched to the makeup tank. Either or both of the primary charging pumps could be operated, depending upon the makeup requirements.

The makeup tank was provided with a recirculation pump and line into which the chemicals for dosing were added using the normal chemical injection pumps. The tank was also provided with a nitrogen sparge line to provide some degree of deoxygenation.

Steam Generator Tube Rupture (SGTR) System -- Two flow lines were installed to simulate the primary to secondary leakage occurring following an SGTR, as shown in Figure 2-11a. These were taken from a warmup line running from the MB-2 T_{hot} inlet to the T_{cold} outlet. Use of this line before each transient test ensured that the SGTR lines contained primary fluid of known chemistry and temperature at the initiation of the test. A calibrated venturi flow meter was installed in the line to measure the primary to secondary leak rate.

The primary to secondary leakage simulation capability was provided at two elevations in the tube bundle. The lower SGTR break element penetrated the lower shell at elevation 57 cm (26.36 in.) and was routed down to elevation 15.2 cm (6.0 in.), where it discharged into the tube bundle on the hot leg side between tube rows 8 and 9, as shown in Figures 2-11a and 2-11b. A flow limiting orifice (0.0935 in. as-built dia., ~ 2.37 mm) was installed in the 5/8 in. (0.495 in. I.D.) line just before the lower shell inlet. Physical obstacles prevented penetration with a straight injection tube at the lower elevation. Thus the flow limiting orifice had to be externally mounted. Downstream of the orifice plate, two-phase flow would exist in all Phase II tests.

The upper SGTR break element penetrated both the lower shell and the wrapper box wall at elevation 716 cm (282 in.), as shown in Figure 2-11a., i.e. ~ 14 cm above the top of the tube bundle (which is at elevation 702 cm, 276 in.). Here the model geometry allowed the use of a straight 5/8 in. (0.495 in. I.D.) injection tube with the flow limiting orifice (0.0938 in. as-built dia., ~ 2.38 mm) located at the top of the tube on the tube bundle centerline (Figure 2-11c). With this installation, flashing would only occur as the primary fluid emerged from the orifice.

2-2-3. Secondary Loop

The secondary system of the facility consists of a model steam generator (MB-2) as the steam supply source, a steam flow system, a condensate system, and a feedwater supply system. In the standard operational mode, the steam leaving the model steam generator passes through an orifice flow meter, through the shell side of the feedwater heater, and into the condenser which it leaves as saturated or slightly subcooled water. The temperature of the condensed water is further lowered in the subcooler before it passes to a 5000-gallon surge tank or to the feedwater pump which circulates the water through the single-stage feedwater heater and back into the downcomer of the model steam generator. Steam and feedwater control valves, flow venturis, pressure transducers and thermocouples are provided to control and monitor the secondary loop. Finally the model boiler is provided with a blowdown line located in the center of the tubesheet at an elevation of 1 cm (0.5 in.). A schematic of the secondary loop flow paths is given in Figure 2-12, and the main equipment specifications are shown in Table 2-2. The MB-2 Phase II Test Program required several modifications to the secondary loop. These are described below.

Stuck-Open Relief Valve (SORV) Lines -- The secondary steam line was modified to provide two additional SORV steam pathways which would simulate either a 2% or an 8% steam flow, as shown schematically in Figure 2-12. In a 4-loop PWR these would be equivalent to the flows escaping to atmosphere via a safety relief valve, when either all 4 steam generators or a single steam generator contributes to the total steam discharge. These two lines originated close to the MB-2 steam exit nozzle and upstream of the main steamline isolation

21

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valve. Each line contained a steam flow limiting orifice (0.386 in. dia. for 8% SORV, 0.193 in. dia. for 2% SORV) and an air-operated isolation valve. These lines joined and then discharged to the SORV condenser. The condenser and piping were located close to the MB-2 steam exit nozzle to minimize the steam transport time. Cooling water to the condenser was provided from the tertiary system by the auxiliary pump. An isometric sketch of the SORV condenser and piping is shown in Figure 2-13. The SORV condensate discharged through a calibrated venturi flowmeter and then drained into a collection tank where the level was measured and recorded. The piping downstream of the condensate venturi was sized such that greater than 25 psig backpressure existed at the condenser. This was necessary to drive the SORV condensate sample flow to the sample station. For the 2% SORV test, the downstream condensate piping was changed from 3/4" O.D. x .050 wall tubing to 3/8 O.D. x .065 wall tubing to provide the necessary backpressure.

Feedwater System -- The introduction of feedwater into the MB-2 has several flow paths depending upon the demanded flow and temperature. The system consists of a main feedwater line and an auxiliary feedwater line coupled with various inlet connections to the model boiler. A schematic of the feedwater system is shown in Figure 2-12.

The auxiliary feedwater line originates at the feedwater pump discharge and bypasses the feedwater heater and thus can only deliver unheated water (90-120°F). The auxiliary feedwater line contains an air operated flow control valve (FCV-299) and a calibrated venturi flowmeter (FE-299) which can measure flow rates up to 2000 lbm/hr. Normal auxiliary feedwater lineup is to the upper shell connection at elevation 401 in. This line was usually sufficient for the 2% SORV tests.

In order to provide the additional feedwater flow required for the 8% and 10% SORV tests, the main feedwater line was employed. This line originates at the feedwater pump and passed through the feedwater heater if required. A bypass line around the feedwater heater is available if unheated water is required. The main feedwater line contains an air operated flow control valve (FCV-201A), a manual throttle valve (HCV-222) and a calibrated venturi flowmeter (FE-201A) usable up to 40,000 lbm/hr. Normal main feedwater lineup

22

is to the MB-2 upper shell connection at elevation 390". This lineup was usually employed for the 8% SORV, 10% SORV and 100% moisture carryover tests. Due to its wide range (0-40,000 lbm/hr), the main feedwater flow venturi had a loss of accuracy at the low flow conditions ($\leq$ 10% of span). To improve the accuracy of the main feedwater flow measurement a smaller calibrated venturi flowmeter (FE-299B) was installed in series with FE-201A. This venturi was identical to the auxiliary feedwater venturi FE-299 and would pass up to 2000 lbm/hr.

Because of the wide range of test conditions required for the Phase II tests, various combinations of feedlines, venturis and inlet connections to the model boiler were used. The lineup for each test is identified in the test performance writeup.

For the transient tests the secondary loop was operated in either of two modified forms of operation. For most transient tests, the exceptions being the two 100% power moisture carryover tests, the secondary loop was operated as a once-through system. In this form of operation water was drawn from the surge tank and was passed via the feedwater system into the MB-2 downcomer. The steam then passed via the 2% or 8% SORV steam lines to the SORV condenser (Figure 2-13) and to the SORV collection tank. For the 100% power moisture carryover tests the secondary loop was operated as described above for standard operations, but with, in addition, the 8% SORV steam flow line open and with additional makeup water being drawn continuously from the surge tank. In all tests chemical dosing solutions (lithium hydroxide or hydrazine) were added to the secondary loop via the auxiliary feedwater line. For the nonvolatile alkali used this ensured that only the MB-2 model boiler was dosed and not the complete loop. During startup the secondary loop was normally dosed via the main feedwater line and in all tests the surge tank was also dosed with chemicals. The single chemical dosing pump was used for all these operations.

The final group of tests were carried out with the dryer bypassed. For these tests the perforated plate which forms the inlet to the dryer was sealed with a welded solid plate. A "D" shaped hole of equivalent area (39.7 in^2.) was then cut in the dryer inlet top plate. By this means steam passed directly to the model boiler steam dome without passing through the dryer.

2-2-4. Tertiary Loop

The tertiary loop forms the cooling water system for both the primary and secondary loops. It provides cooling water for the cooling tower, condenser, subcooler, primary pump, feedwater pump bearings and recirculation line, nonregenerative heat exchanger moisture probe and the isokinetic and chemical sample coolers. For the Phase II tests it was only necessary to modify this loop slightly, so that it also supplied the SORV condenser mounted beside the model boiler and the additional chemical sample lines installed for the tests. A schematic of the tertiary loop flow paths is included in Figure 2-11d.

2-2-5. Chemical Sampling System

The complete test facility is provided with a number of chemical sample lines from each of the three loops. These pass to a central sampling room where they are cooled and sampled. For the Phase II tests these sample points were only used for the routine monitoring of the loops during startup and pretest operation.

For the transient tests five additional sampling lines were installed. These were taken from the primary loop, the model boiler (3 samples) and the SORV condensate. No sample was taken from the auxiliary feedwater line as this only contained demineralized water dosed with hydrazine. Each sample line was cooled locally and then run in small bore stainless steel tubing, to reduce transit times, to an air-conditioned sample hut sited at the foot of the tower housing the MB-2 model boiler. Here each sample line was provided with an isolation valve, a ten-turn flow control valve and an additional cooling coil immersed in a bath containing flowing city water. The four principal sample lines were then routed to in-line conductivity cells and finally to sample collection points which flowed continuously into a common drain. The overflow from the cooling bath was arranged so that it flushed the drain continuously and an internal divider was provided to segregate the low-level SORV condensate sample from other sample streams, hence minimizing cross contamination. The outputs from the conductivity monitors were fed to two chart recorders in the hut and to the Data General computer system in the main control room. An overall schematic drawing of this system is shown in Figure 2-14; details of the individual sample lines are given below.

Primary Sample Point -- The primary sample was taken from the SGTR warmup line at a point close to the hot leg inlet to the model boiler and immediately downstream of the isolation valve in the warmup line. The sample line was piped in 1/4-inch stainless steel tubing to a standard cooler (Parker, size 6) and then in 1/8-inch stainless steel tubing to the sample hut 12 to 15 feet away. The cooler fitted to this line was of a counterflow double coil design having an inner coil of 3/8-inch outside diameter; its internal volume was approximately 200 ml. The overall volume of the sample line up to the inlet of the conductivity cell was 465 ml.

Model Boiler Sample Points -- Twelve sample points were available in the MB-2 model boiler, namely the steam sampling points S-1 to S-6 and the isokinetic sample points IKP-1 to IKP-6 located within the tube bundle. In addition, samples could be taken from the model boiler blowdown line. Of these, two were selected as the main sample points, while a blowdown sample line was installed for use in one series of tests.

Of the sample points installed in the upper section of the model boiler, sample points S-2 to S-6 lay above the primary separator; S-2 within the shroud, S-3 to S-5 in the entrance to the dryers and S-6 at the exit to the model boiler. These, therefore, could not be used to sample the model boiler water under normal operating conditions. The remaining sample point, S-1, was located in the downcomer below the swirl vane (elevation 1143 to 1194 cm, 450 to 470 in.), but still above the level of the auxiliary feedwater inlet at elevation 1018 cm (401 in.). This sample point should therefore see water essentially identical in composition to that of the entrained droplets passing through the primary separator and should provide the most representative sample for determining carryover; it was selected as the principal sample point for tests at normal water level. Physically, the sample point consisted of a 1/4-inch stainless steel tube which entered the downcomer at elevation 1072 cm (422 in.) and which had a 3-inch vertical section pointing upwards into the downcomer flow; the top elevation was thus at 1080 cm (425 in.).

The isokinetic sample points IKP-1 to IKP-6 all lay within the tube bundle between rows 6 and 7 and between columns 2 and 3. They were located at elevations 153, 357 and 561 cm (60.25, 140.50 and 220.88 in.), there being a sample point in the hot and the cold legs at each level. In each case the sample point was a 1/4-inch stainless steel tube having a 3-inch vertical section pointing down into the flow. Since the bottom break SGTR line entered the tube bundle wrapper on the hot leg side and since voidage will increase with elevation, the cold leg sample point at elevation 153 cm (60.25 in.), designated IKP-4, was used as the second sampling point. As there is a flow distribution baffle (elevation 51 cm (20.0 in.)) between the bottom break SGTR line and the sample point, it was expected that good mixing would occur under most conditions.

The blowdown sample point was taken from the 3/4-inch blowdown line at a point ~ 125 inches downstream from the base of the model boiler. This sample line and those taken from sample points S-1 and IKP-4 were piped in 1/4-inch stainless steel tubing to an adjacent sample cooler and from there in 1/8-inch stainless steel tubing to the sample hut (Figure 2-14). The maximum length of any sample line was about 50 feet (S-1). Both the blowdown and IKP-4 sample lines used coolers identical to that fitted to the primary sample line, but that fitted to the S-1 sample point (Parker, size 4) was of smaller size, 1/4-inch outside diameter tubing, and volume ~ 75 ml. The calculated volume of the blowdown sample line from the blowdown inlet within the model boiler to the collection point was 1212 ml. For the S-1 and IKP-4 sample lines the measured volumes from the model boiler shell to the collection points were 172 and 492 ml, respectively, while the estimated volumes within the model boiler were 38 and 37 ml. Hence the overall volumes were 172 ml (S-1) and 529 ml (IKP-4).

SORV Condensate Sample Point -- Steam from the 2% and 8% SORV lines was condensed and then passed through a flow measurement venturi in a loop seal U-tube before passing to the collection tank. The sample was taken from the base of the U-tube and run in 1/4-inch stainless steel tubing first to a sample cooler and from there directly to the sample hut; again the sample cooler was identical to that used on the primary sample. For this sample a larger bore sample line was installed since only a small pressure head was available to drive the sample flow. The measured volume of this sample line was 690 ml.

TABLE 2-1

DOWNCOMER VOLUME/AREA COMPARISON

	Component	MB-2 Configuration	Model F
VOLUMES m^3 (ft^3)			
a.	Upper downcomer	0.148 (5.24)	19.47 (687)
b.	Secondary separator disengagement pipe, J-tube, and extension	0.011 (0.38)	-
c.	Downcomer funnel	0.025 (0.89)	-
d.	Downcomer "dead space"	-	-
e.	Downcomer pipes and ducts	0.087 (3.09)	12.89 (455)
f.	Total	0.272 (9.60)	32.36 (1142)
VOLUME RATIOS			
a.	$\frac{\text{Upper downcomer}}{\text{Lower downcomer}}$	2.11	1.51
b.	$\frac{\text{Lower downcomer}}{\text{Secondary bundle}}$	0.29	0.29
c.	$\frac{\text{Total downcomer}}{\text{Secondary bundle}}$	0.89	0.73
MB-2 CROSS-SECTIONAL AREAS m^2 (ft^2)			
a.	Upper downcomer (typical)	0.086 (0.93)	
b.	Lower downcomer pipes	0.009 (0.10)	

TABLE 2-2

TEST LOOP EQUIPMENT SPECIFICATIONS

Item	Specification
Primary Pump	0.0674 m^3/s at 128 m (1068 GPM, 420 ft. Head)
Primary Heater No. 1 and No. 3	3.5 MWt (12 x 10^6 Btu/hr) (each)
Primary Heater No. 4	10 MWt (34 x 10^6 Btu/hr)
Primary Charging Pump No. 1	2.6 x 10^{-4} m^3/s (4.1 GPM)
Primary Charging Pump No. 2	5.0 x 10^{-4} m^3/s (8.0 GPM)
Pressurizer Relief Pressure	17.2 Mpa (2500 psig)
Primary Heater No. 4 Relief Pressure	20.7 Mpa (3000 psig)
Feedwater Pump	5.24 - 6.5 x 10^{-3} m^3/s (83-103 GPM, 2725-2850 ft. Head)
Chemical Addition Pump	5.6 x 10^{-6} m^3/s (0-5.3 GPH) (Two units, each system)
Cooling Tower	0.236 m^3/s, 40-30°C at 27° wet bulb (3740 GPM (105° to 85°F at 80°F wet bulb))
Circulating Pump	0.252 m^3/s (4000 GPM, 32 ft. Head)
Condenser Pump	0.143 m^3/s (2260 GPM, 91 ft. Head)
Subcooler Pump	0.0934 m^3/s (1480 GPM, 111 ft. Head)
Auxiliary Cooling Pump	0.0189 m^3/s (300 GPM, 230 ft. Head)
Steam Generator Relief Pressure	8.27 Mpa (1200 psig)
Condenser Relief Pressure	4.03 Mpa (585 psig)
Feedwater Heater Relief Pressure	11.4 Mpa (1650 psig)

2-3. REFERENCES

1. M. Y. Young, K. Takeuchi, O. J. Mendler, and G. W. Hopkins, Prototypical Steam Generator (MB-2) Transient Testing Program, NUREG/CR-3661, EPRI NP-3494, WCAP-10475 (1984).

29

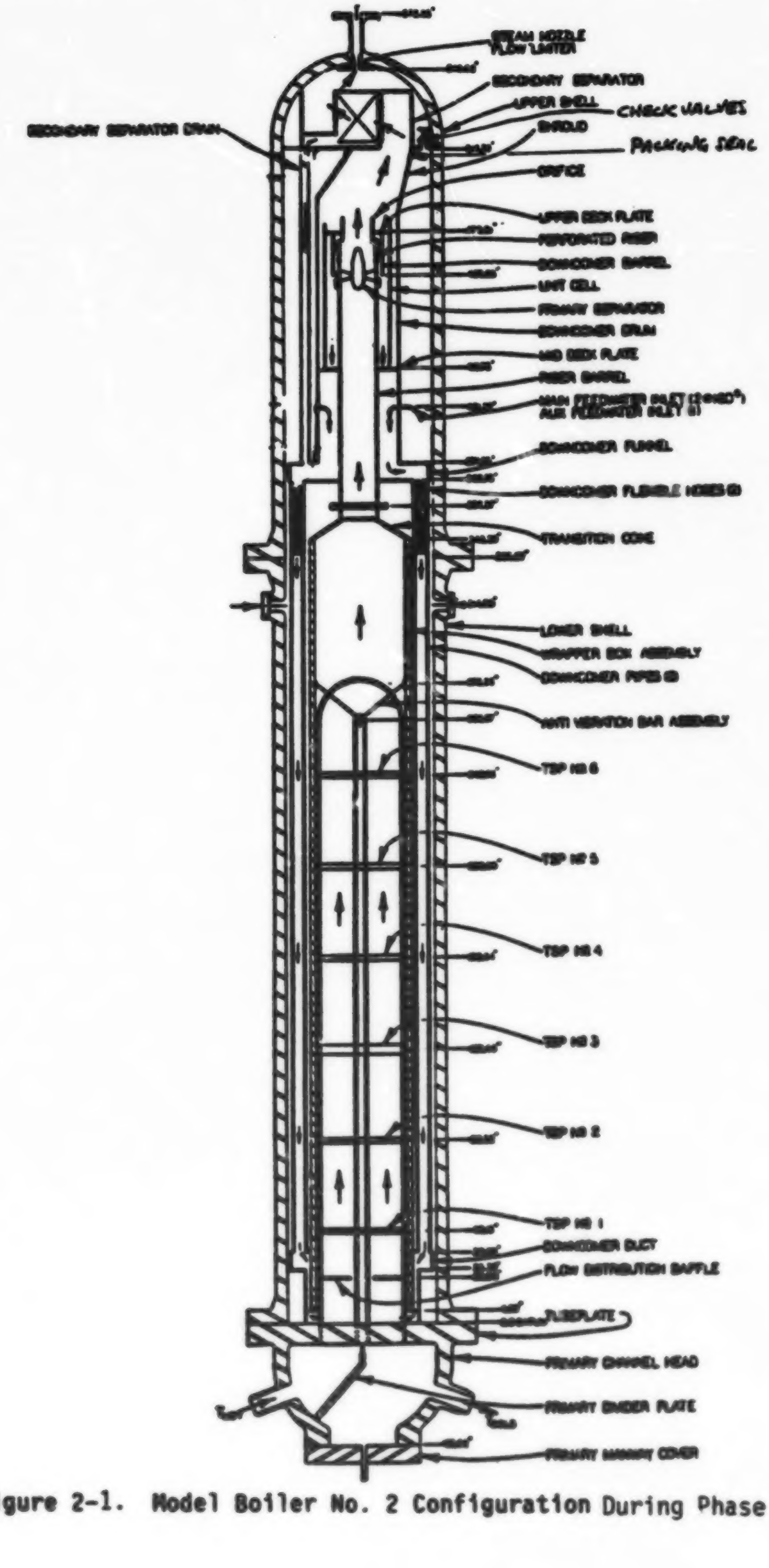
STEAM NOZZLE FLOW LIMITER
SECONDARY SEPARATOR
UPPER SHELL
CHECK VALVES
SHROUD
PACKING SEAL
SECONDARY SEPARATOR DRAIN
ORIFICE
UPPER DECK PLATE
PERFORATED RISER
DOWNCOMER BARREL
UNIT CELL
PRIMARY SEPARATOR
DOWNCOMER DRUM
MID DECK PLATE
RISER BARREL
MAIN FEEDWATER INLET
AUX FEEDWATER INLET
DOWNCOMER FUNNEL
DOWNCOMER FLEXIBLE HOSES
TRANSITION CONE
LOWER SHELL
WRAPPER BOX ASSEMBLY
DOWNCOMER PIPES
ANTI VIBRATION BAR ASSEMBLY
TSP NO 6
TSP NO 5
TSP NO 4
TSP NO 3
TSP NO 2
TSP NO 1
DOWNCOMER DUCT
FLOW DISTRIBUTION BAFFLE
TUBEPLATE
PRIMARY CHANNEL HEAD
PRIMARY DIVIDER PLATE
PRIMARY MANWAY COVER

Figure 2-1. Model Boiler No. 2 Configuration During Phase II Tests

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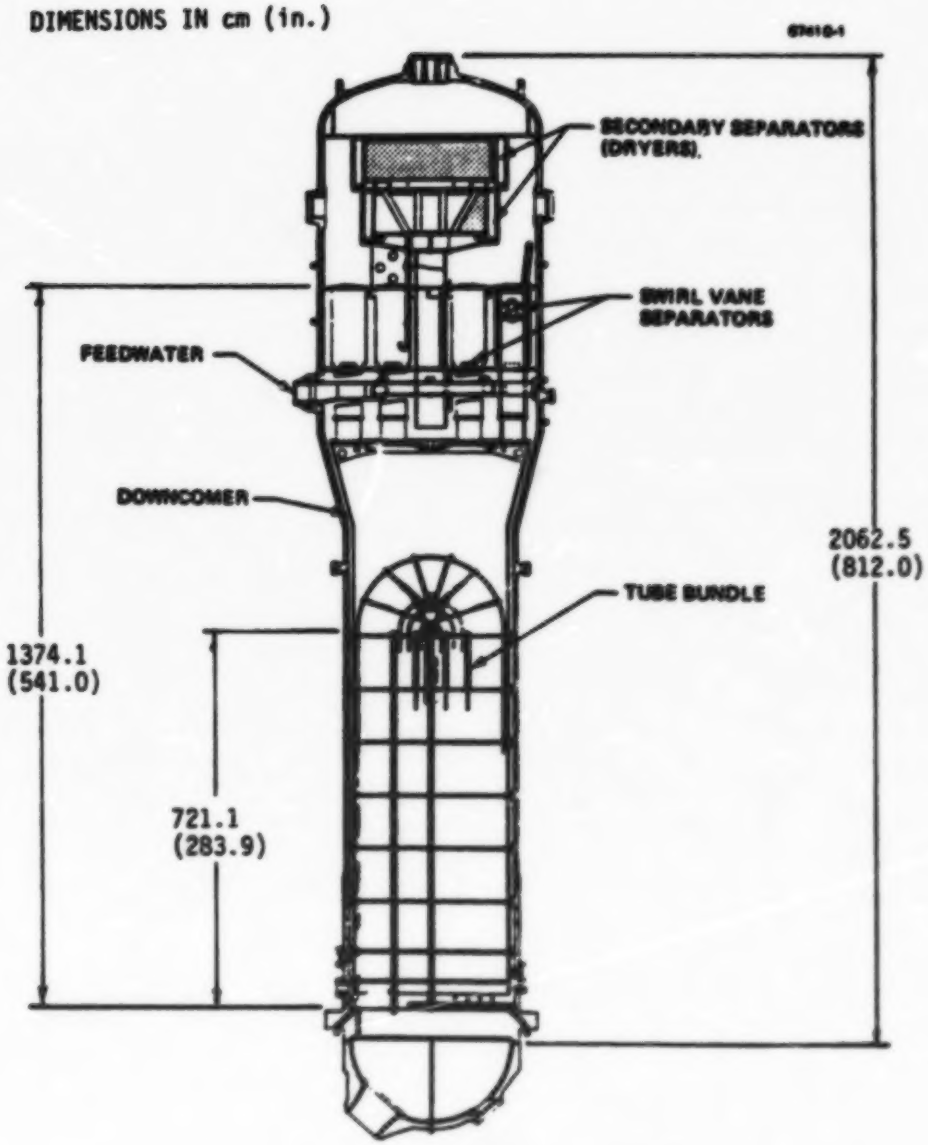

DIMENSIONS IN cm (in.)
67410-1
SECONDARY SEPARATORS (DRYERS)
SWIRL VANE SEPARATORS
FEEDWATER
DOWNCOMER
TUBE BUNDLE
2062.5 (812.0)
1374.1 (541.0)
721.1 (283.9)

Figure 2-2. Westinghouse Model F Steam Generator

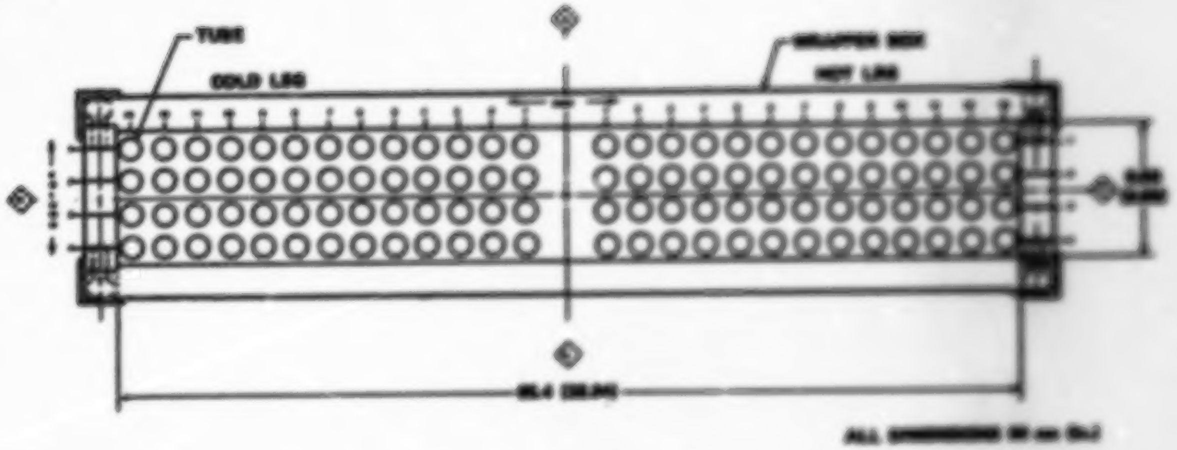
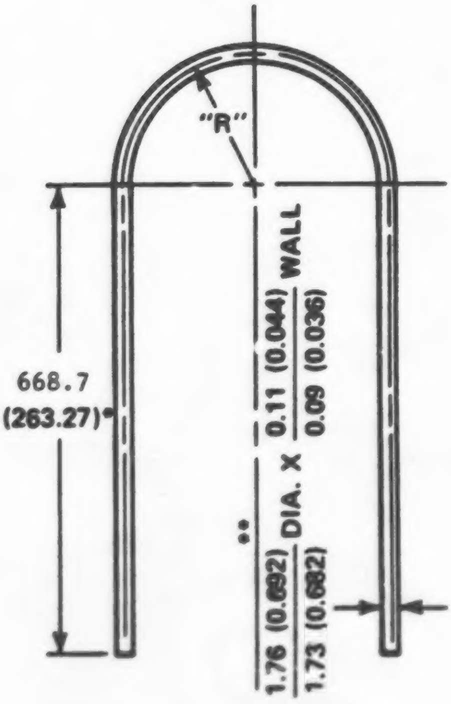

TUBE
COLD LEG
WRAPPER BOX
HOT LEG
ALL DIMENSIONS IN cm (in.)

Figure 2-3. MB-2 Bundle Cross-Section

6741C-2

ROW	"R" cm (in.)
1	3.10 (1.22)
2	5.59 (2.200)
3	8.08 (3.180)
4	10.57 (4.160)
5	13.06 (5.140)
6	15.54 (6.120)
7	18.03 (7.100)
8	20.52 (8.080)
9	23.01 (9.060)
10	25.50 (10.040)
11	27.99 (11.020)
12	30.48 (12.000)
13	32.97 (12.980)


"R"
668.7
(263.27)*
** 1.76 (0.692) / 1.73 (0.682) DIA. X 0.11 (0.044) / 0.09 (0.036) WALL

* MEASURED FROM TOP OF TUBESHEET

** MAXIMUM / MINIMUM DRAWING TOLERANCE

Figure 2-4. MB-2 U-Tube Dimensions

33

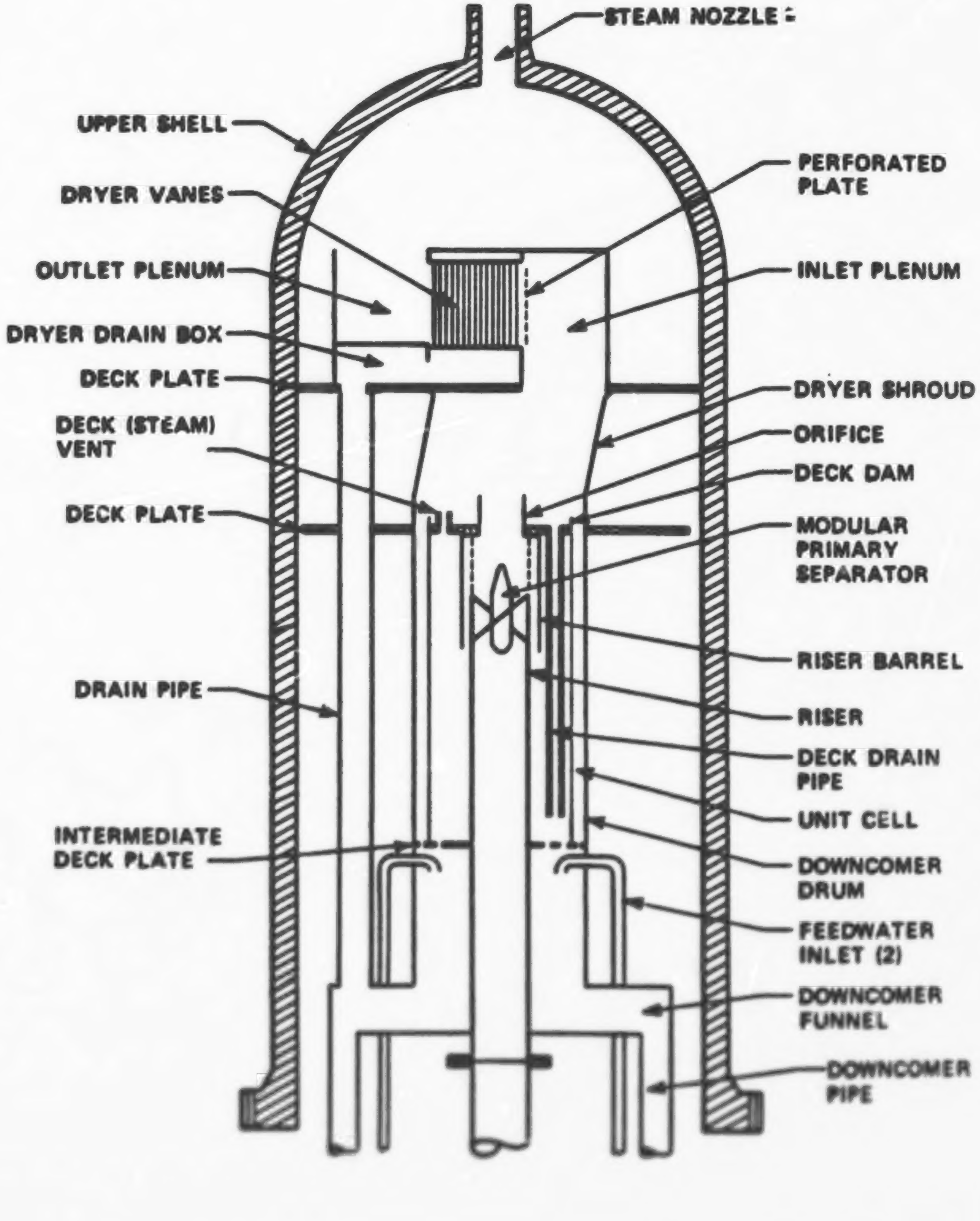

STEAM NOZZLE
UPPER SHELL
PERFORATED PLATE
DRYER VANES
OUTLET PLENUM
INLET PLENUM
DRYER DRAIN BOX
DECK PLATE
DRYER SHROUD
DECK (STEAM) VENT
ORIFICE
DECK DAM
DECK PLATE
MODULAR PRIMARY SEPARATOR
RISER BARREL
DRAIN PIPE
RISER
DECK DRAIN PIPE
UNIT CELL
INTERMEDIATE DECK PLATE
DOWNCOMER DRUM
FEEDWATER INLET (2)
DOWNCOMER FUNNEL
DOWNCOMER PIPE

Figure 2-5. MB-2 Upper Shell Region

8741C-6

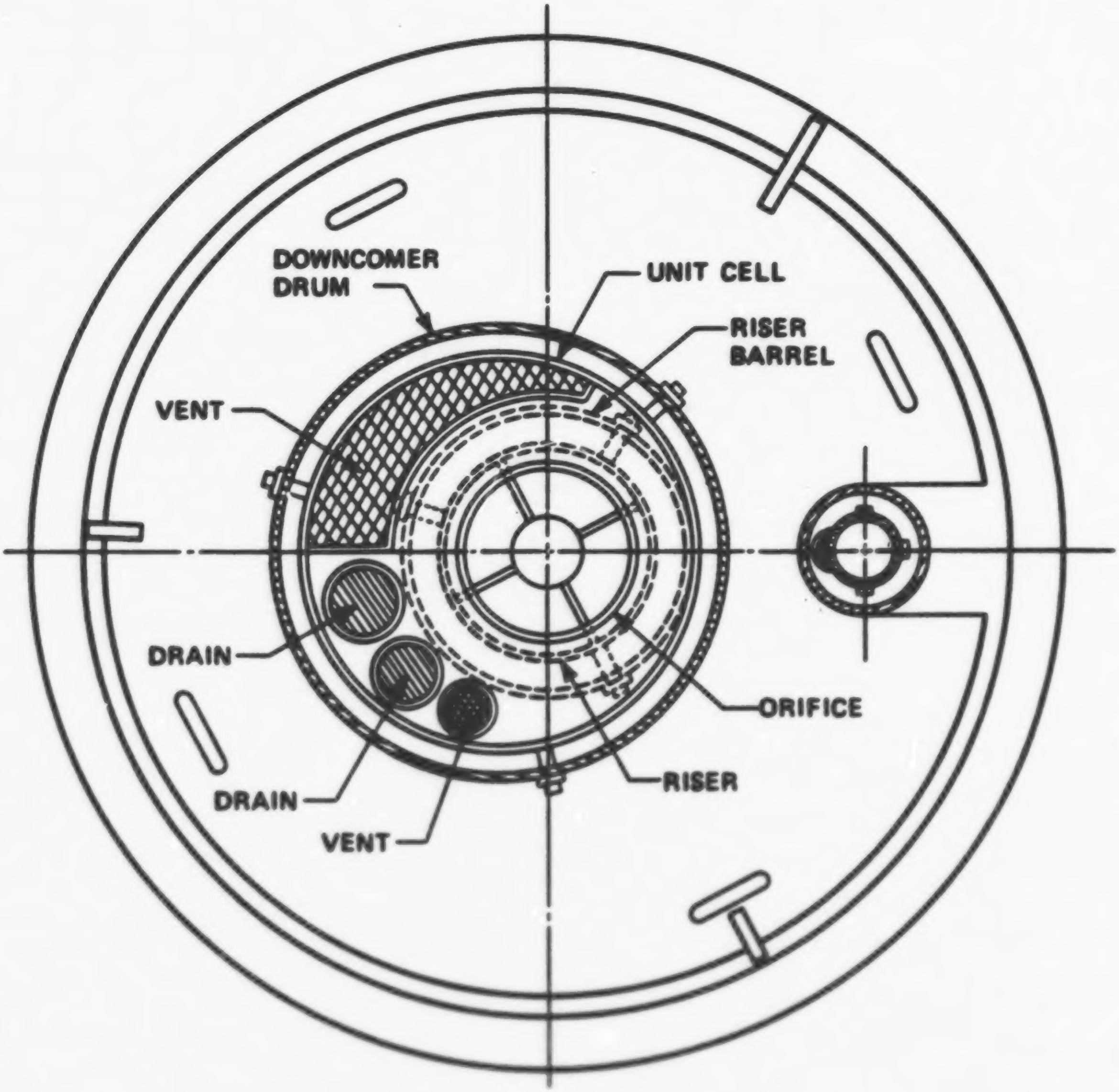

DOWNCOMER DRUM
UNIT CELL
RISER BARREL
VENT
DRAIN
ORIFICE
DRAIN
RISER
VENT

Figure 2-6. MB-2 Cross-Section at Deck Plate
(Elevation 477.01 in.)

95

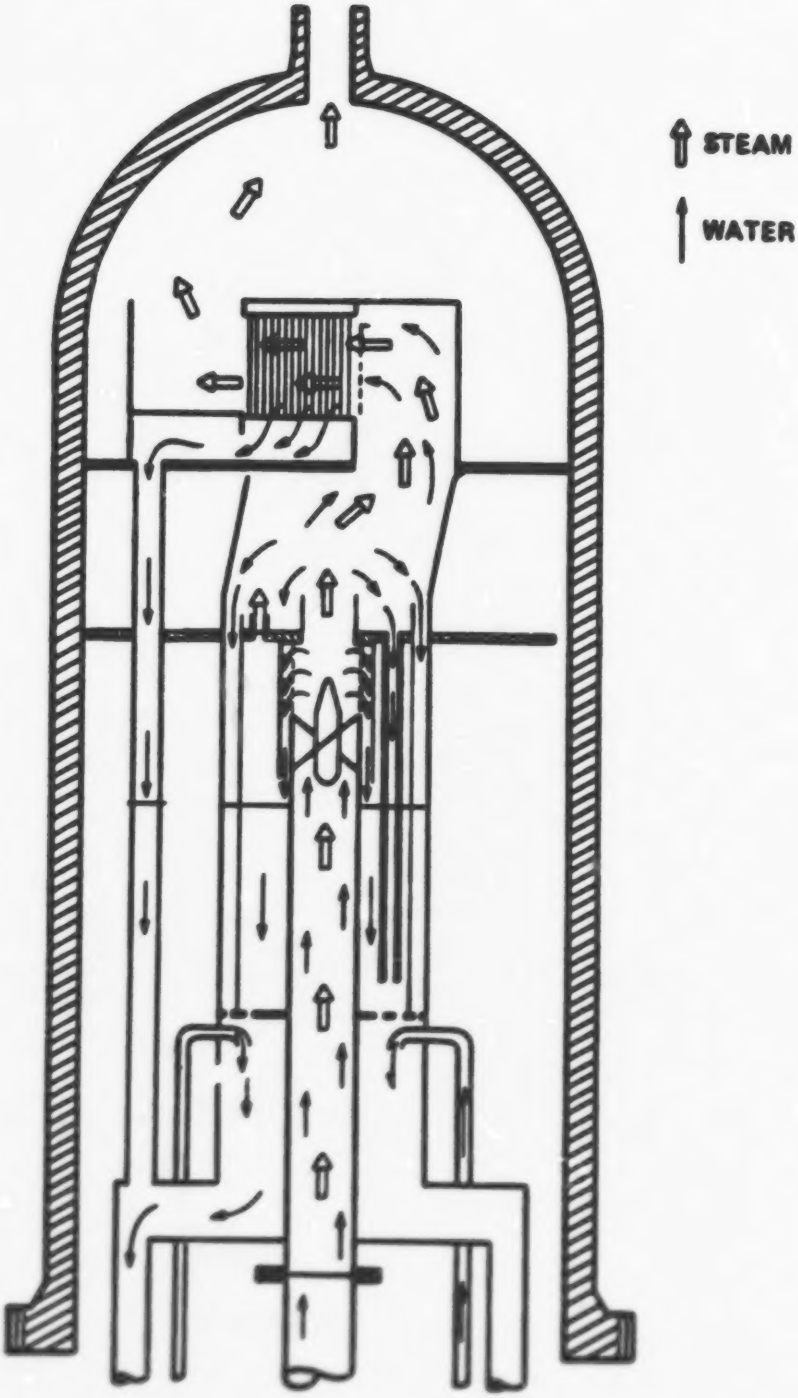

STEAM
WATER

Figure 2-7. Flow Paths in MB-2 Upper Shell Region

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32

6741C-6

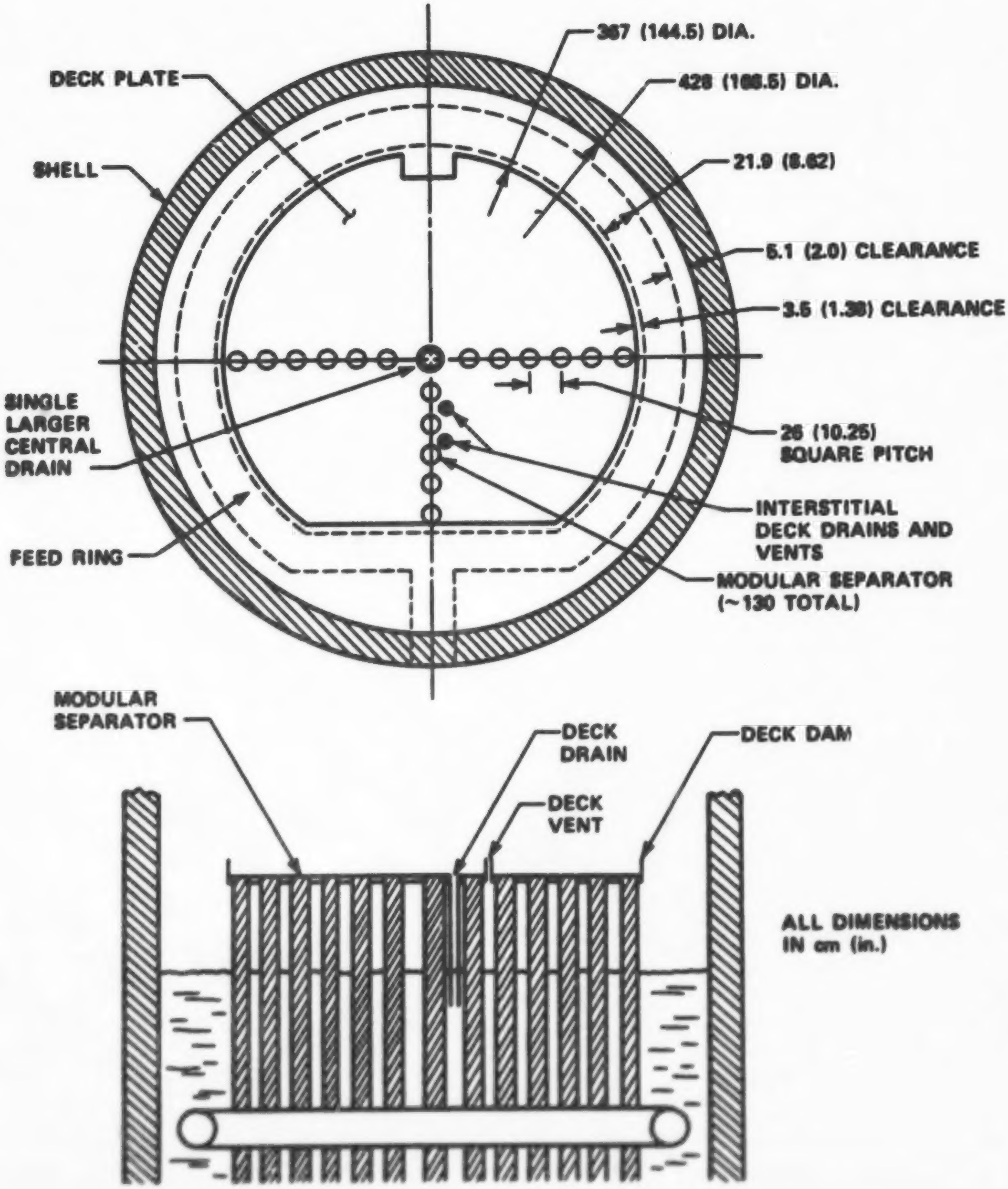
367 (144.5) DIA.
DECK PLATE
428 (168.5) DIA.
SHELL
21.9 (8.62)
5.1 (2.0) CLEARANCE
3.5 (1.38) CLEARANCE
SINGLE LARGER CENTRAL DRAIN
26 (10.25) SQUARE PITCH
INTERSTITIAL DECK DRAINS AND VENTS
FEED RING
MODULAR SEPARATOR (~130 TOTAL)
MODULAR SEPARATOR
DECK DRAIN
DECK DAM
DECK VENT
ALL DIMENSIONS IN cm (in.)

Figure 2-8. Modular Separators Configured in a Model F Shell

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37

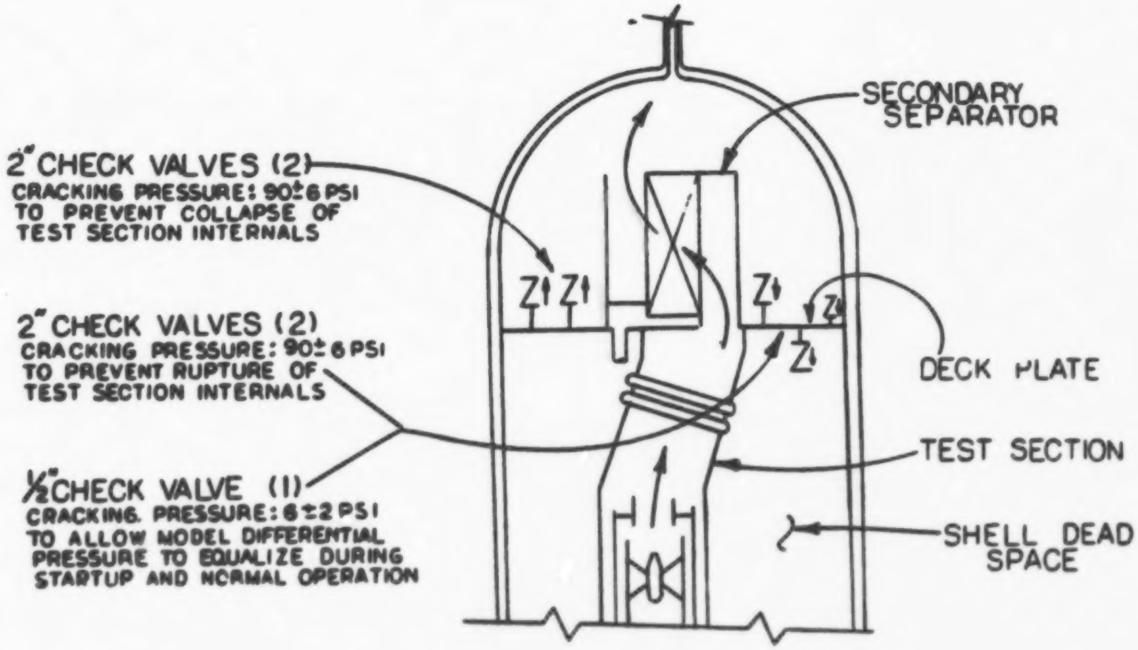
SECONDARY SEPARATOR
2" CHECK VALVES (2)
CRACKING PRESSURE: 90±6 PSI
TO PREVENT COLLAPSE OF TEST SECTION INTERNALS
2" CHECK VALVES (2)
CRACKING PRESSURE: 90±6 PSI
TO PREVENT RUPTURE OF TEST SECTION INTERNALS
DECK PLATE
TEST SECTION
½" CHECK VALVE (1)
CRACKING PRESSURE: 6±2 PSI
TO ALLOW MODEL DIFFERENTIAL PRESSURE TO EQUALIZE DURING STARTUP AND NORMAL OPERATION
SHELL DEAD SPACE

Figure 2-9. MB-2 Internal Check Valves

58

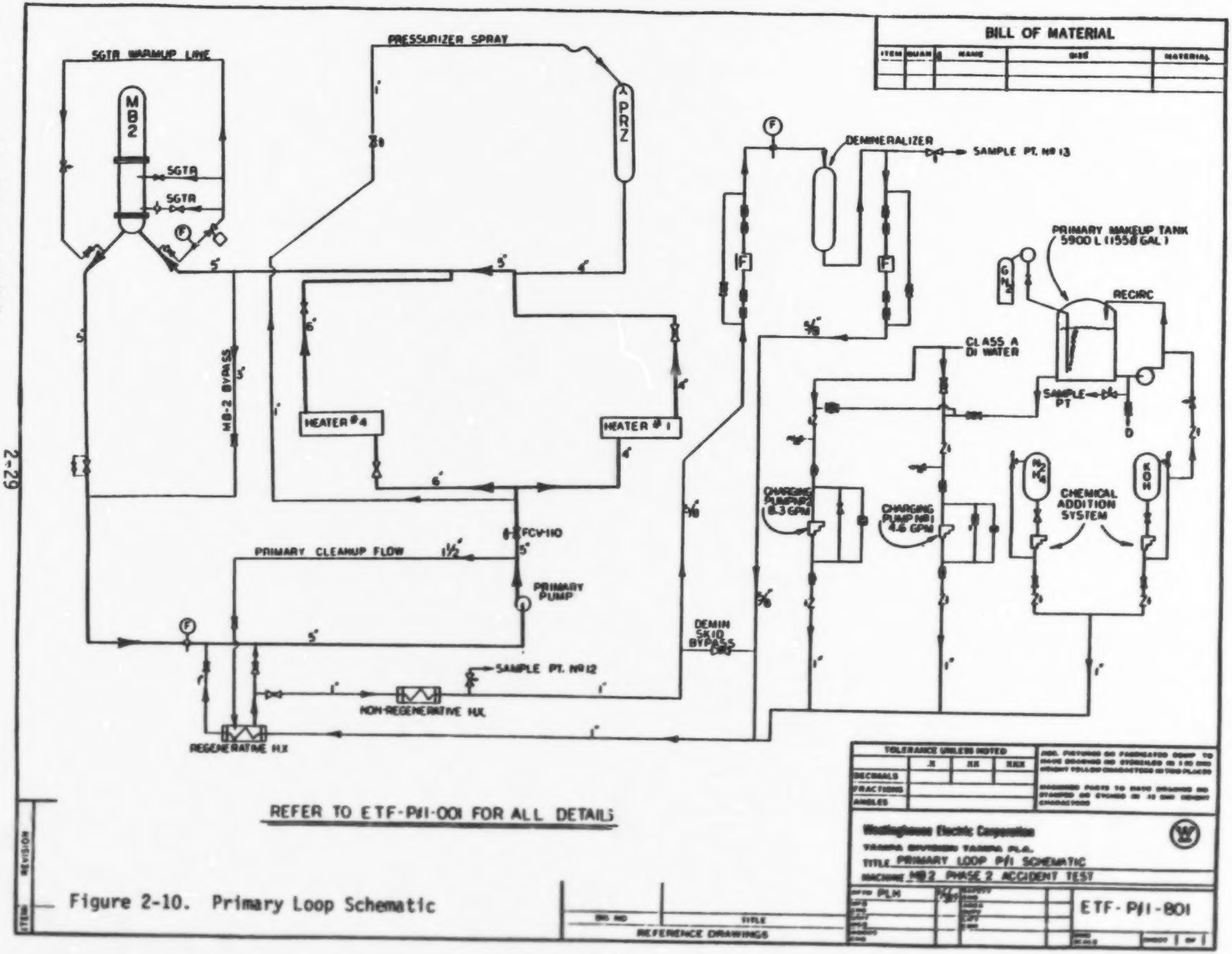
BILL OF MATERIAL
ITEM
QUAN
NAME
SIZE
MATERIAL
SGTR WARMUP LINE
MB2
SGTR
SGTR
F
PRESSURIZER SPRAY
1"
PRZ
5"
5"
4"
6"
4"
HEATER #4
HEATER #1
4"
6"
5"
3"
MB-2 BYPASS
1"
FCV-110
5"
PRIMARY CLEANUP FLOW
1½"
PRIMARY PUMP
F
5"
SAMPLE PT. NO 12
1"
1"
1"
NON-REGENERATIVE HX
1"
REGENERATIVE HX
1"
DEMIN SKID BYPASS
⅜"
⅜"
⅜"
F
DEMINERALIZER
SAMPLE PT. NO 13
F
F
PRIMARY MAKEUP TANK
5900 L (1558 GAL)
GN2
RECIRC
CLASS A DI WATER
SAMPLE PT
D
CHARGING PUMP NO 2 8.3 GPM
CHARGING PUMP NO 1 4.6 GPM
N2H4
KOH
CHEMICAL ADDITION SYSTEM
1"
1"
1"
REFER TO ETF-P/I-001 FOR ALL DETAILS
TOLERANCE UNLESS NOTED
.X
.XX
.XXX
DECIMALS
FRACTIONS
ANGLES
Westinghouse Electric Corporation
TAMPA DIVISION TAMPA FLA.
TITLE PRIMARY LOOP P/I SCHEMATIC
MACHINE MB2 PHASE 2 ACCIDENT TEST
PLH
ETF-P/I-801
REVISION
ITEM
DWG NO
TITLE
REFERENCE DRAWINGS
SHEET
OF

Figure 2-10. Primary Loop Schematic

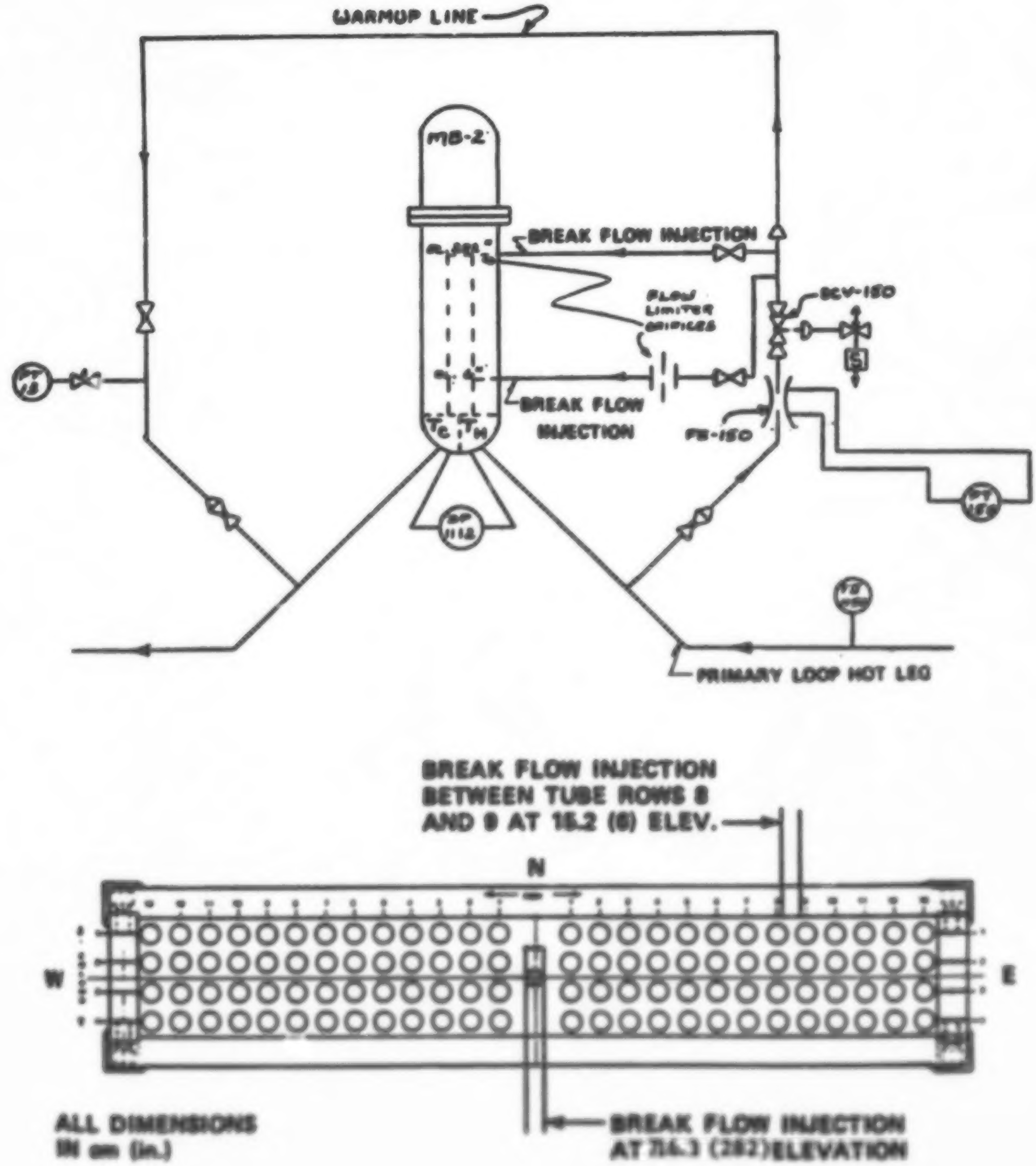
WARMUP LINE
MB-2
BREAK FLOW INJECTION
FLOW LIMITER ORIFICES
SCV-150
S
PT 13
BREAK FLOW INJECTION
FE-150
T_C
T_H
DP 1112
PRIMARY LOOP HOT LEG
BREAK FLOW INJECTION BETWEEN TUBE ROWS 8 AND 9 AT 15.2 (6) ELEV.
N
W
E
ALL DIMENSIONS IN cm (in.)
BREAK FLOW INJECTION AT 716.3 (282) ELEVATION

Figure 2-11a. Loop Modifications for SGTR Tests

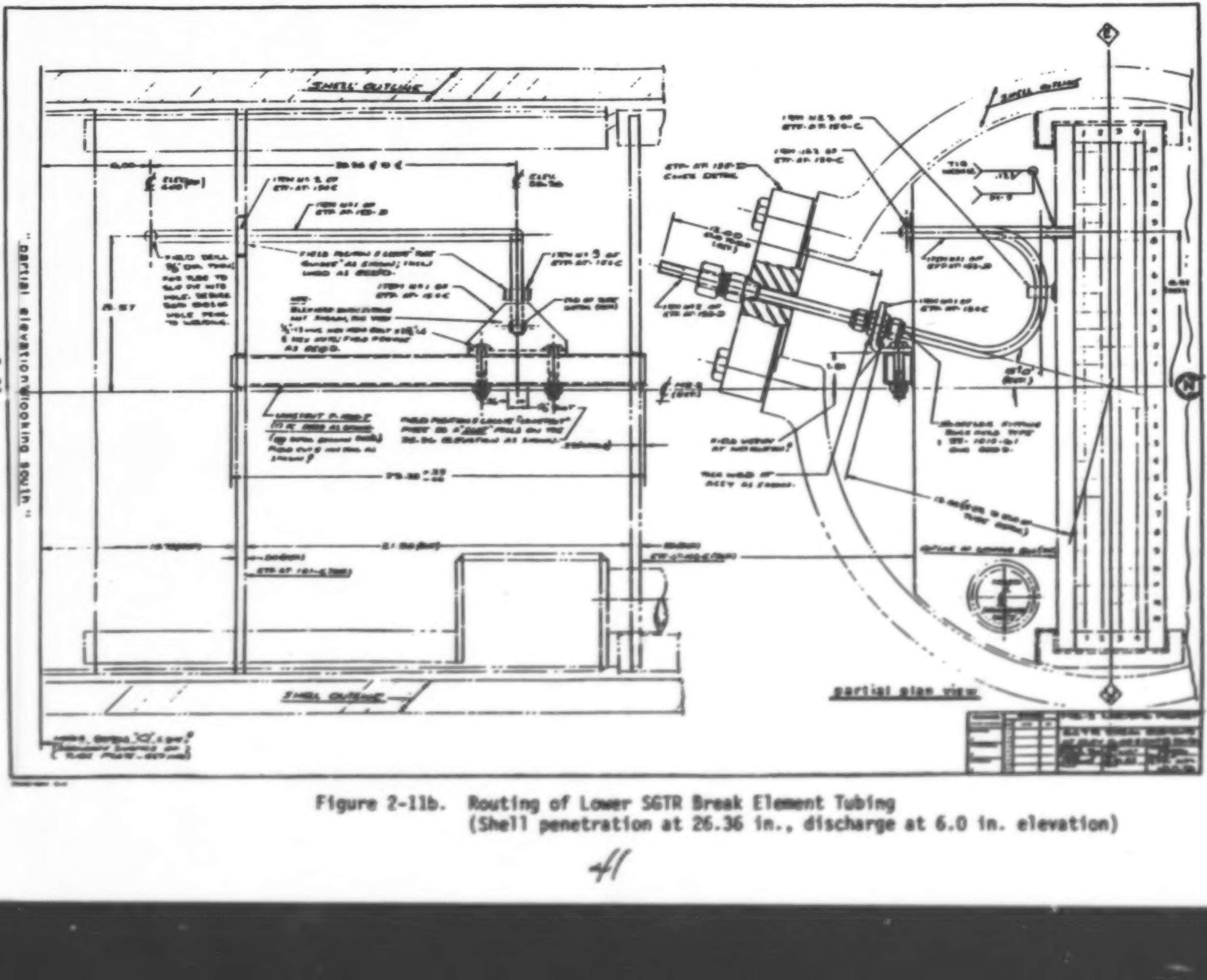
partial elevation looking south
SHELL OUTLINE
SHELL OUTLINE
SHELL OUTLINE
partial plan view

Figure 2-11b. Routing of Lower SGTR Break Element Tubing
(Shell penetration at 26.36 in., discharge at 6.0 in. elevation)

41

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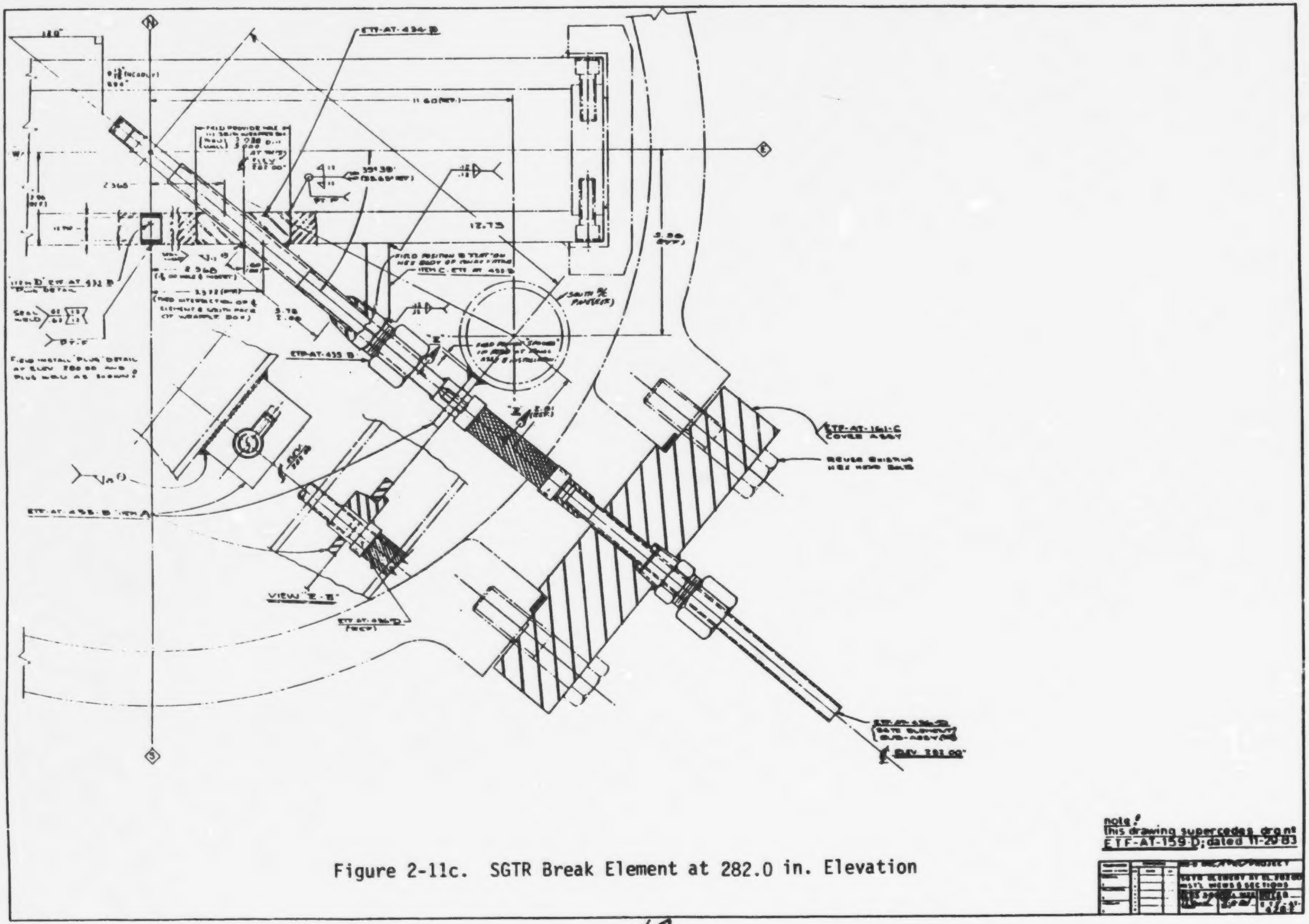
ETF-AT-434-B
11.60(REF)
12.75
ETF-AT-435-B
VIEW "Z-Z"
ETF-AT-161-C COVER ASSY
REUSE EXISTING HEX HEAD BOLTS
note!
this drawing supercedes drg no
ETF-AT-159-D; dated 11-29-83

Figure 2-11c. SGTR Break Element at 282.0 in. Elevation

42

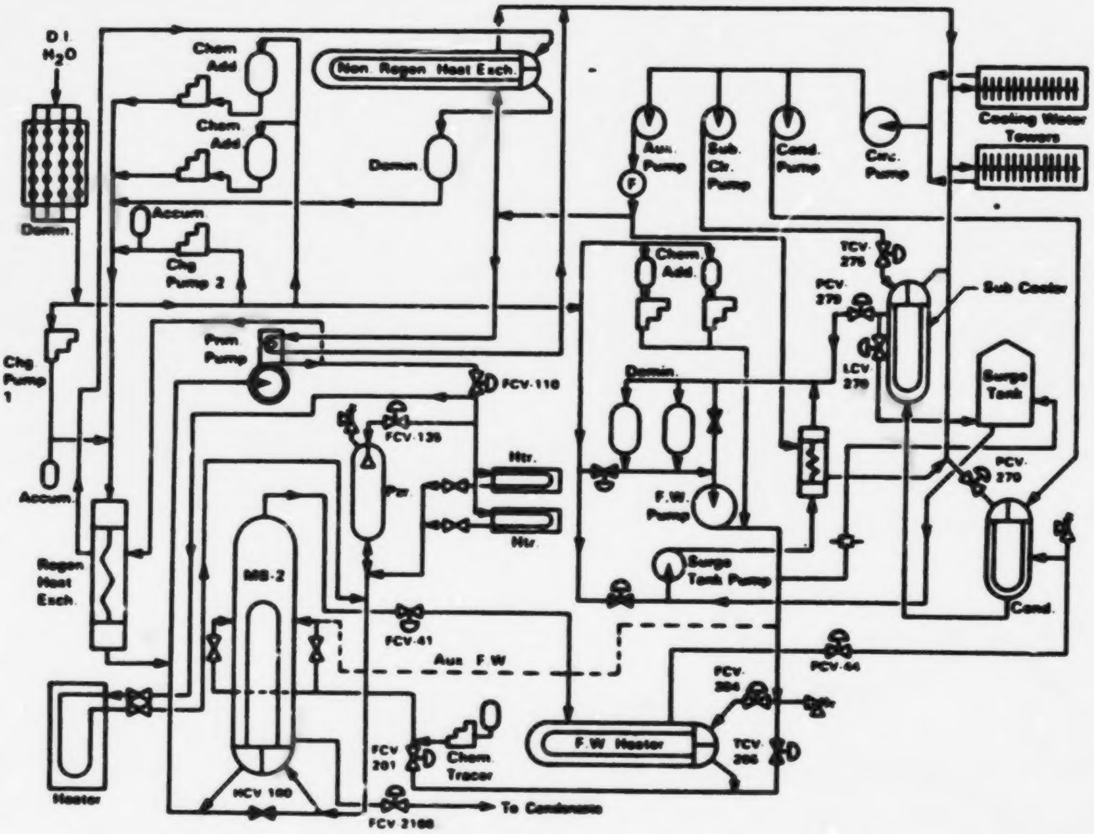
D.I.
H_2O
Demin.
Chem Add
Chem Add
Non. Regen. Heat Exch.
Demin.
Accum.
Chg Pump 2
Chg Pump 1
Accum.
Prim. Pump
FCV-110
FCV-136
Htr.
Htr.
Pzr.
Regen Heat Exch.
MB-2
FCV-41
Aux. F.W.
Heater
HCV 100
FCV 201
Chem. Tracer
FCV 2100
To Condensate
F.W. Heater
FCV 204
TCV 206
PCV-64
Aux. Pump
F
Sub. Clr. Pump
Cond. Pump
Circ. Pump
Cooling Water Towers
Chem. Add.
Demin.
F.W. Pump
Surge Tank Pump
TCV 270
PCV 270
LCV 270
Sub Cooler
Surge Tank
PCV 270
Cond.
6741C-3

Figure 2-11d. Schematic of Tertiary Loop
(See Figures 2-10 and 2-12 for Updated Schematics of the Primary and Secondary Loops)

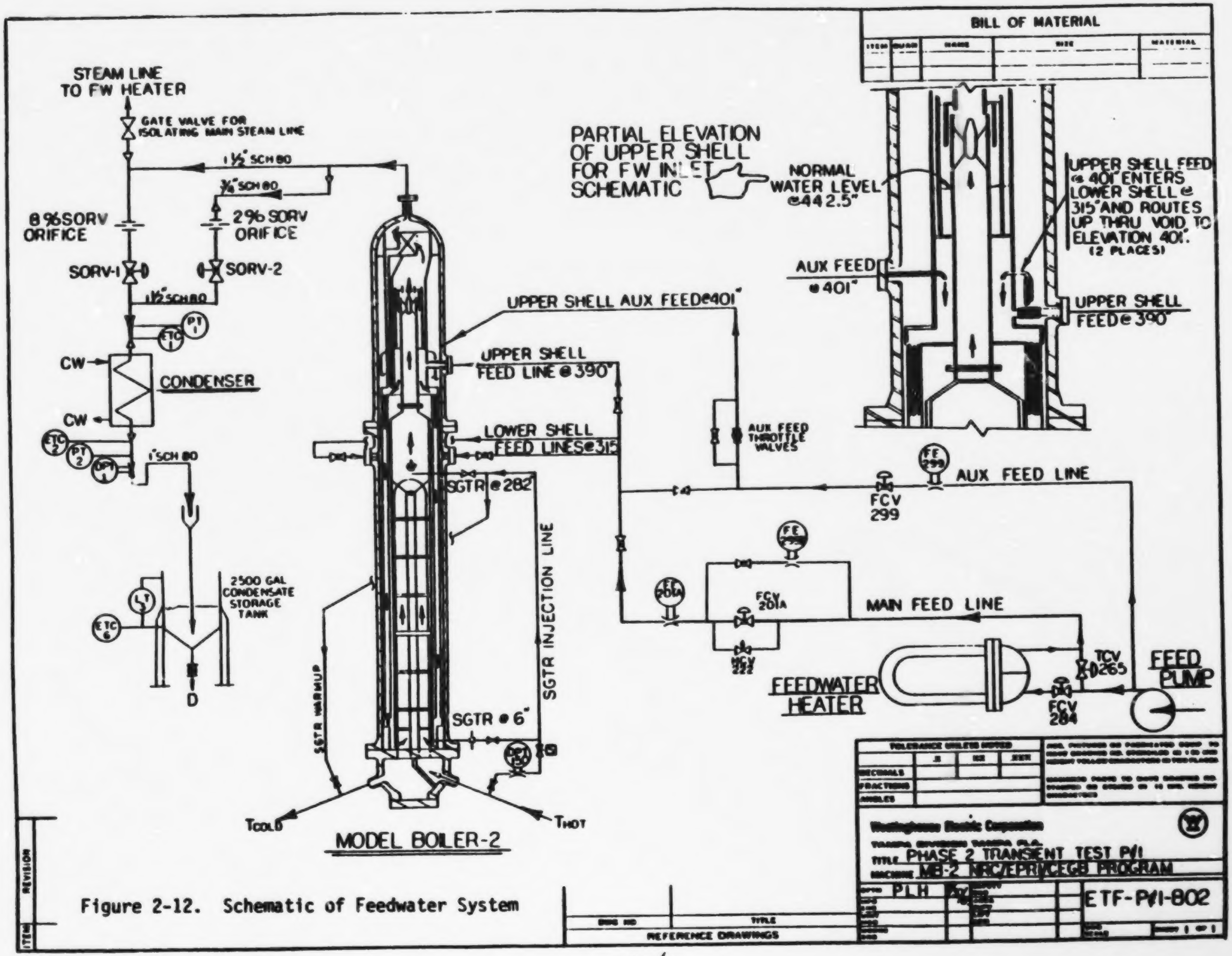
BILL OF MATERIAL
ITEM
NAME
SIZE
MATERIAL
STEAM LINE TO FW HEATER
GATE VALVE FOR ISOLATING MAIN STEAM LINE
1½" SCH 80
¾" SCH 80
8% SORV ORIFICE
2% SORV ORIFICE
SORV-1
SORV-2
1½" SCH 80
PT 1
ETC 1
CW
CONDENSER
CW
ETC 2
PT 2
DPT 1
1" SCH 80
2500 GAL CONDENSATE STORAGE TANK
LT 3
ETC 6
D
PARTIAL ELEVATION OF UPPER SHELL FOR FW INLET SCHEMATIC
NORMAL WATER LEVEL @442.5"
UPPER SHELL FEED @ 401" ENTERS LOWER SHELL @ 315" AND ROUTES UP THRU VOID TO ELEVATION 401". (2 PLACES)
AUX FEED @401"
UPPER SHELL FEED @ 390"
UPPER SHELL AUX FEED @401"
UPPER SHELL FEED LINE @ 390"
LOWER SHELL FEED LINES @ 315"
AUX FEED THROTTLE VALVES
SGTR @ 282"
SGTR INJECTION LINE
SGTR WARMUP
SGTR @ 6"
DPT 12
FE 299
AUX FEED LINE
FCV 299
FE
FE 201A
FCV 201A
MAIN FEED LINE
HCV 222
TCV 265
FCV 284
FEED PUMP
FEEDWATER HEATER
TCOLD
THOT
MODEL BOILER-2
TOLERANCE UNLESS NOTED
DECIMALS
FRACTIONS
ANGLES
Westinghouse Electric Corporation
TITLE PHASE 2 TRANSIENT TEST P/I
MACHINE MB-2 NRC/EPRI/CEGB PROGRAM
PLH
ETF-P/I-802
REFERENCE DRAWINGS
DWG NO
TITLE
REVISION
ITEM

Figure 2-12. Schematic of Feedwater System

44

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1. ALL DIMENSIONS ARE TO CENTER OF FLANGES, REDUCERS
2. LINE SIZES CHANGE AT REDUCERS ONLY (▶)
3. LINE SIZES ARE INDICATED BY NUMBERS WITHIN CIRCLES
4. PIPE SCHEDULES ARE AS FOLLOWS
   - (a) 1½" SCH 80
   - (b) 2" SCH 160
   - (c) ¾" SCH 80
   - (d) 3" SCH 80

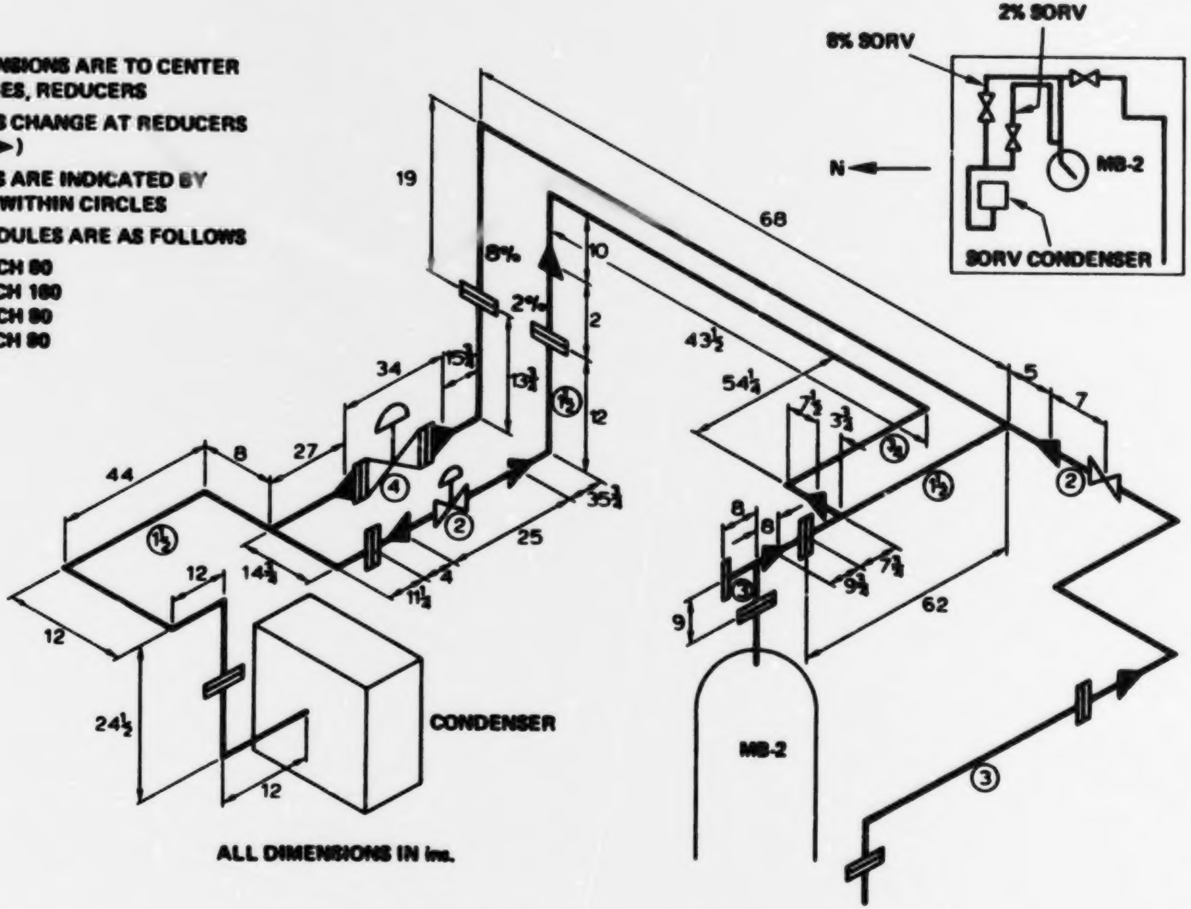
2% SORV
8% SORV
N
MB-2
SORV CONDENSER
19
68
8%
2%
10
2
12
43½
54¼
34
15½
13¾
7½
3¾
5
7
44
8
27
④
②
③
1½
35¾
25
8
8
14¾
4
11¼
9¾
7¼
12
12
62
9
24½
12
CONDENSER
MB-2
ALL DIMENSIONS IN ins.
KG/MCJ(30.7.80)RL 5.1.1980

Figure 2-13. Isometric Sketch of SORV Piping and Condenser

45

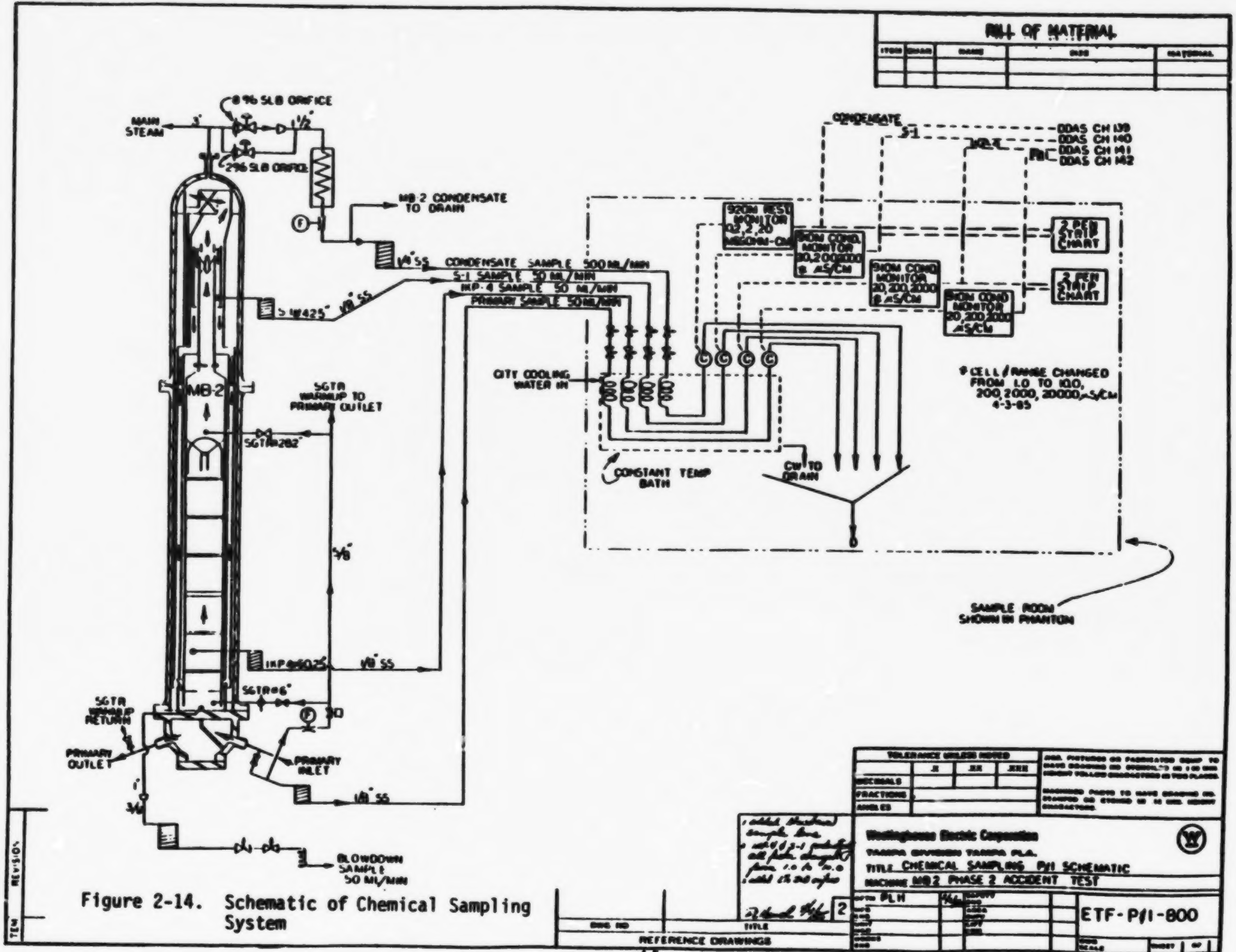
BILL OF MATERIAL
ITEM
MATERIAL
MAIN STEAM
3"
8.96 SLB ORFICE
2.96 SLB ORFICE
1½"
MB-2 CONDENSATE TO DRAIN
F
1/4" SS
CONDENSATE SAMPLE 500 ML/MIN
S-1 SAMPLE 50 ML/MIN
IKP-4 SAMPLE 50 ML/MIN
PRIMARY SAMPLE 50 ML/MIN
S 1@425"
1/4" SS
CONDENSATE
S-1
IKP-4
PRI
DDAS CH 139
DDAS CH 140
DDAS CH 141
DDAS CH 142
920M REST MONITOR .02,.2,2,20 MEGOHM-CM
910M COND. MONITOR 20,200,2000 * μS/CM
910M COND MONITOR 20,200,2000 * μS/CM
910M COND MONITOR 20,200,2000 μS/CM
2 PEN STRIP CHART
2 PEN STRIP CHART
C
C
C
C
CITY COOLING WATER IN
CONSTANT TEMP BATH
CW TO DRAIN
* CELL / RANGE CHANGED FROM 1.0 TO 10.0, 200, 2000, 20000 μS/CM 4-3-85
SAMPLE ROOM SHOWN IN PHANTOM
MB-2
SGTR WARMUP TO PRIMARY OUTLET
SGTR@282"
5/8"
IKP4@60.25"
1/8" SS
SGTR@6"
F
SGTR WARMUP RETURN
PRIMARY OUTLET
PRIMARY INLET
1"
3/4"
1/4" SS
BLOWDOWN SAMPLE 50 ML/MIN
TOLERANCE UNLESS NOTED
DECIMALS
FRACTIONS
ANGLES
Westinghouse Electric Corporation
TAMPA DIVISION TAMPA FLA.
TITLE CHEMICAL SAMPLING P&I SCHEMATIC
MACHINE MB2 PHASE 2 ACCIDENT TEST
PLH
ETF-P&I-800
2
DWG NO
TITLE
REFERENCE DRAWINGS
SHEET
OF

Figure 2-14. Schematic of Chemical Sampling System

SECTION 3

TEST FACILITY INSTRUMENTATION

3-1. TUBE BUNDLE

The instrumentation of the model boiler tube bundle consisted of thermocouples, pressure transmitters and differential pressure transmitters.

3-1-1. Thermocouples

The MB-2 tube bundle was instrumented with 106 thermocouples to measure the temperatures of the primary fluid, secondary fluid, and the tube wall near its outer surface. The temperatures recorded by these thermocouples can be used to calculate local heat fluxes and heat transfer coefficients for both the primary and secondary sides of the tubes. The thermocouples were positioned at various axial and radial locations in the bundle. They extend axially from just above the tubesheet surface up to the U-bend and radially from tube rows 3 through 12.

The overall distribution of the thermocouples was selected considering the experience gained in previous model test programs, in particular the FLECHT SEASET natural circulation tests (1). The distribution of thermocouples shown in Figure 3-1, is such that a relatively large portion of the total number were located near the bottom of the generator where the cold feedwater flow enters the bundle. It was expected that the maximum temperature differences, the highest heat fluxes, and the largest tube-to-tube differences would occur at the bottom of the bundle. Differences in boiling regimes (subcooled and saturated) were also expected in this region due to the crossflow nature of the feedwater. In addition, since the power was to be significantly less than the full-power capability of the generator for several of the tests, the majority of the heat would be transferred at the bottom of the bundle. At the lowest elevations the thermocouples were radially positioned within three "super cells" in each leg of the bundle (Figure 3-2). The super cells have been defined for the purpose of analyzing the temperature measurements. It is assumed that all the tubes in a cell behave the same so the data from adjacent tubes can be used to obtain the heat flux distribution for each cell.

The higher elevations in the tube bundle contained a smaller fraction of the total number of thermocouples and, therefore, a coarser distribution existed. As shown in Figures 3-1 and 3-2, in the hot leg the thermocouple strings present in the three super cells near the bottom of the bundle were redistributed radially, such that only two super cells existed near the top of the bundle. In the cold leg, a single super cell was utilized above the 127 cm (50 in.) elevation. At higher elevations it is believed that the flow is more one-dimensional (axial) within each leg, therefore, less radial detail was required. The lower heat fluxes which were expected at the higher elevations, particularly during low power operation and when the bundle was uncovered during water level reductions, also permitted greater spacing of the thermocouples.

All bundle thermocouples were routed through the south wrapper box wall and from there out to the shell penetrations. Figures 3-3 to 3-5 illustrate the various configurations which were used for mounting the thermocouples to the tubes and for routing them through the bundle to the wrapper box wall. As shown, guide tubes having a 0.32 cm (1/8 in.) OD were used to enclose the PTC (primary thermocouple) and STC (secondary thermocouple) leads, protecting them from potential damage caused by crossflow.

The tube bundle thermocouples were premium grade, chromel/constant (Type E) thermocouples, having "Special Limits of Error" for the thermocouple and extension wires. The sheaths were fabricated from Inconel 600. All thermocouples had ungrounded hot junctions to provide electrical isolation from interference and stray noise. As shown in Figure 3-6, both the PTC's and STC's had 0.157 cm (0.062 in.) sheath O.D.'s. The TTC's (tube wall thermocouples) included a transition in the sheath diameter. Over a short length near the sensing tip the diameter was 0.051 cm (0.020 in.) while the remainder was 0.102 cm (0.040 in). The 0.051 cm (0.020 in.) diameter sensing tip of the TTC's was embedded in a machined slot in the tube so that the hot junction was nominally positioned 0.041 cm (0.016 in.) below the tube outer surface. All thermocouples were calibrated by the vendor at a number of temperatures which covered the expected operating range during the transient tests (94° to 330°C, 200° to 625°F).

48

As stated previously, the temperature measurements made within a super cell can be used to determine the local heat flux and heat transfer coefficients. For this, the heat flux is first determined from the measured primary temperature difference over an axial span within the cell. Next, having the measured tube wall temperature for one of the tubes within the cell, the heat transfer coefficient on the inside surface of the tube can be calculated. The tube wall temperature, along with the measured secondary fluid temperature in the cell, may then be used to calculate the heat transfer coefficient on the tube outer surface.

3-1-2. Pressure Taps and Differential Pressure Measurements

The secondary side of the tube bundle included nine static pressure taps located on the south wrapper box wall. The taps extended axially from a point just below the flow distribution baffle to an elevation 25.4 cm (10 in.) above the top of the bundle (Figure 3-7 and Table 3-1). They were spaced so that a tap was positioned within each support span of the tube bundle. As a result, the differential pressure measurements obtained using these taps include the loss associated with each support plate (Table 3-2). In addition, an absolute pressure measurement was made at tap P07 to determine the bundle steam pressure.

49

TABLE 3-1

LOCATION OF MB-2 TUBE BUNDLE PRESSURE TAPS

Secondary Side	Tap	Elevation Above Tubesheet cm (in.)	Radial Location
	P01	43.18 (17.00)	Hot leg between rows 6 and 7
	P02	66.95 (26.36)	Hot leg between rows 6 and 7
	P03	131.62 (51.82)	Hot leg between rows 6 and 7
	P08A	213.36 (84.0)	Hot leg between rows 6 and 7
	P08	284.02 (111.82)	Hot leg between rows 6 and 7
	P09	322.12 (126.82)	Hot leg between rows 6 and 7
	P04A	416.56 (164.00)	Hot leg between rows 6 and 7
	P04	493.24 (194.19)	Hot leg between rows 6 and 7
	P05	599.33 (235.96)	Hot leg between rows 6 and 7
	P06	637.44 (250.96)	Hot leg between rows 6 and 7
	P07	727.94 (286.59)	Opposite tube lane

TABLE 3-2

TUBE BUNDLE DIFFERENTIAL PRESSURE MEASUREMENTS

Secondary Side	Identification	Location/Measurement
	DP-0102	Flow distribution baffle
	DP-0203	Tube support plate No. 1
	DP-0308	Tube support plate No. 2
	DP-0809	Tube support plate No. 3
	DP-0904	Tube support plate No. 4
	DP-0405	Tube support plate No. 5
	DP-0506	Tube support plate No. 6
	DP-0607	U-bend
	DP-0107	Total bundle
	DP-0404A	Between support plates No. 4 and No. 5
	DP-0808A	Between support plates No. 2 and No. 3

3-2. LOWER DOWNCOMER

3-2-1. Pressure Taps and Differential Pressure Measurements

A number of pressure taps were included in both the hot and cold leg downcomer pipes to obtain measurements of the water level, recirculation flow rates, and differential pressures. Table 3-3 and Figure 3-8 identify the locations of the pressure taps. Table 3-4 lists the differential pressure measurements which were obtained during the transient tests.

As shown in Table 3-4, three differential pressure (DP) measurements were made in the hot leg downcomer pipe for the purpose of determining the water level--one for top, middle, and bottom sections of the pipe.

Separate DP measurements were also provided in each downcomer pipe to determine the recirculation flow rates. These measurements were made using the existing Pitot-static probes which had previously been used for flow measurement over the normal operating power range (15-100 percent of full power).

Differential pressure measurements were also made in each leg to determine the pressure drop in the downcomer duct and through the wrapper opening into the bottom of the tube bundle.

An additional DP measurement was also made to provide an indication of the amount of condensate that had collected on the tubesheet in the dead space between the wrapper box and the shell (DP-9914).

TABLE 3-3

LOCATION OF PRESSURE TAPS IN MB-2 LOWER DOWNCOMER REGION

Tap	Location	Elevation Above Tubesheet cm (in.)
P42	Hot leg downcomer pipe	2.54 (1.0)
P21	Hot leg downcomer pipe	36.83 (14.5)
P19	Hot leg downcomer pipe	103.6 (40.8)
P31	Hot leg downcomer pipe	243.3 (95.8)
P30	Hot leg downcomer pipe	247.1 (97.3)
P23	Hot leg downcomer pipe	635.0 (250.0)
P92	Hot leg downcomer pipe	848.4 (334.0)
P22	Cold leg downcomer pipe	36.83 (14.5)
P20	Cold leg downcomer pipe	103.6 (40.8)
P33	Cold leg downcomer pipe	243.3 (95.8)
P32	Cold leg downcomer pipe	247.1 (97.3)
P99	Dead space	98.60 (38.82)
P14	Dead space	-10.80 (-4.25)

TABLE 3-4

LOWER DOWNCOMER REGION DIFFERENTIAL PRESSURE MEASUREMENTS

Identification	Location/Measurement
DP-9219	Hot leg water level (middle)
DP-1942	Hot leg water level (bottom)
DP-9223	Hot leg water level (top)
DP-3031	Hot leg downcomer flow (Pitot-static probe 1)
DP-3233	Cold leg downcomer flow (Pitot-static probe 1)
DP-1901	Hot leg downcomer duct + wrapper opening
DP-2001	Cold leg downcomer duct + wrapper opening
DP-9914	Tubesheet dead space condensate level

52

3-2-2. Thermocouples

The determination of the water level in the hot leg downcomer pipe from differential pressure measurements requires a knowledge of the axial distribution of the density of the downcomer fluid. This density information can be determined from temperature measurements in the downcomer pipes. Since the downcomer fluid was expected to experience a wide variation in temperature during these transient tests, a number of thermocouples were provided. As shown in Figure 3-8 and Table 3-5, four downcomer thermocouples (DTCs) were positioned at elevations of 118.1, 368.3, 609.6 and 825.5 cm. (46.5, 145, 240 and 325 in.) in the hot leg downcomer; a further two were provided in the cold leg pipe at 118.1 and 825.5 cm (46.5 and 325 in.). The fluid densities determined from the lowest thermocouple readings may also be used in the calculation of the downcomer flow rates.

In addition to the thermocouples installed within the downcomer pipes, additional temperature measurements were made in the lower shell "dead space," external to the pipes and wrapper box. Two thermocouples, DTC-5A and DTC-6A, were used to measure the temperature of the dead space fluid (steam for the Phase II transient tests) at elevations of 131.62 and 637.5 cm (51.82 and 251.0 in.), respectively. These thermocouples were mounted on the I-beam supporting the south wrapper box wall. Four other thermocouples were embedded in the outside surface of the south wrapper box wall at two elevations, on both the hot leg and cold leg sides. Two were located at the 127 cm (50.00 in) elevation and two at the 637.5 cm (251.00 in.) elevation. The purpose of these wrapper box wall and dead space thermocouples was to provide a means of establishing heat transfer through the walls of the wrapper box and into the dead space. The locations of these thermocouples are given in Tables 3-6 and 3-7 and are shown in Figure 3-9.

TABLE 3-5

DOWNCOMER PIPE FLUID THERMOCOUPLES (DTCs)

Elevation Above Tubesheet cm (in.)	Hot Leg Downcomer Pipe	Cold Leg Downcomer Pipe
118.1 (46.5)	DTC-2	DTC-4
368.3 (145.0)	DTC-9	
609.6 (240.0)	DTC-10	
825.5 (325.0)	DTC-7A	DTC-8A

TABLE 3-6

"DEAD SPACE" FLUID THERMOCOUPLES (DTCs)

Elevation Above Tubesheet cm (in.)	Thermocouple
131.6 (51.82)	DTC-5A
637.5 (251.00)	DTC-6A

TABLE 3-7

WRAPPER BOX WALL THERMOCOUPLES (WTCs)

Elevation Above Tubesheet cm (in.)	Hot Leg Side	Cold Leg Side
127. (50.00)	WTC-1	WTC-3
637.5 (251.00)	WTC-2	WTC-4

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54

3-3. UPPER SHELL REGION

3-3-1. Pressure Taps and Differential Pressure Measurements

A total of 15 pressure taps were provided in the upper shell region to obtain differential pressure measurements a) for the pressure losses through the various components and flow paths, b) for determining the water level, and c) for determining the drain flow from the secondary separator. The locations of the pressure taps are defined in Table 3-8 and Figure 3-10. The differential pressure measurements obtained during the accident tests are listed in Table 3-10.

Two principal water level measurements were made. Of these a wide range differential pressure measurement (DP-9321) was made to determine the secondary water level during the initial filling of the boiler and during transient tests at reduced levels. For most tests at more normal water levels the narrow range measurement (DP-9368) was used to determine the water level in the upper downcomer region; this latter signal was transmitted to the computer for water level control. In those tests where the dryer was flooded, an additional measurement (DP-8069) was used to determine the water level at high levels.

The remainder of the differential pressure measurements was used to obtain the pressure drop along the major flow paths in the upper shell region. These include losses up through the primary separator riser, across the swirl vane, through the primary separator orifice, the gravity separation region between the separators, and through the secondary separator.

Other paths included the return path through the downcomer and through the secondary separator drain box and pipe. The total pressure drop between the top of the tube bundle and the steam generator exit was measured with DP-0791. Note, however, that absolute pressure measurements were also obtained from taps 07 and 91.

3-3-2. Thermocouples

Two thermocouples were included in the upper downcomer water volume for use in determining the fluid density needed in the water level calculations. Figure 3-10 and Table 3-9 identify these thermocouples. As shown in Figure 3-10, one thermocouple, DTC-11, was located below the feedwater inlet and indicated the temperature of the feedwater/recirculated fluid mixture. The second, DTC-12, was located above the feedwater inlet and measured the temperature of the recirculated (saturated) water which was returned from the separators. Three thermocouples (STC-60, STC-61 and STC-62) were installed to monitor fluid temperatures in the riser and the steam dome during transient tests (Figure 3-10).

TABLE 3-8

LOCATION OF PRESSURE TAPS IN MB-2 UPPER SHELL REGION

Tap	Elevation Above Tubesheet cm (in.)
60	973.3 (383.2)
61	1074.4 (423.0)
62	1204.7 (474.3)
65	1204.7 (474.3)
68	973.1 (383.1)
69	1224.3 (482.0)
80	1340.9 (527.9)
81	1340.9 (527.9)
82	1313.9 (517.3)
83	1079.5 (425.0)
87	1026.2 (404.0)
88	1221.7 (481.0)
91	1427.0 (561.8)
93	1290.3 (508.0)
94	1295.4 (510.0)

TABLE 3-9

LOCATION OF UPPER DOWNCOMER THERMOCOUPLES

Elevation Above Tubesheet cm (in.)	Thermocouple
965.2 (380) (below feedwater inlet)	DTC-11
1041.4 (410) (above feedwater inlet)	DTC-12

TABLE 3-10

UPPER SHELL REGION DIFFERENTIAL PRESSURE MEASUREMENTS

Identification	Location/Measurement
DP-0760	Bundle plenum to riser transition
DP-6061	Primary separator riser
DP-6165	Primary separator total
DP-6269	Primary separator orifice
DP-6569	Deck plate
DP-6980	Steam shroud and secondary separator inlet
DP-8081	Secondary separator
DP-0791	Tube bundle to S/G exit
DP-6869	Upper downcomer
DP-6892	Downcomer funnel
DP-8281	Secondary separator drain box
DP-8887	Secondary separator drain pipe
DP-9321	Wide range downcomer water level
DP-9368	Narrow range downcomer water level
DP-9914	Shell void water level

57

3-4. LOOP INSTRUMENTATION

A number of measurements were made in both the primary and secondary loops to monitor and control the pressures, temperatures, and flows among the various components. Figure 3-11 presents a schematic identifying the loop measurements which were of interest in evaluating the performance of the MB-2 model during the accident tests. For clarity, additional measurements in the remainder of the loop and various subsystems have not been shown.

Considering first the instrumentation in the primary loop, platinum resistance temperature detectors (RTD's) were used to measure both the inlet and outlet primary fluid temperatures to the model (T-1150 and T-1250). The primary flow to the model was determined using either an annubar and two ranges of differential pressure transducers (DP-109) or, at low flow rates, a venturi tube (FE-111). The flow measurement was made in the cold leg piping. In addition, the pressure in the primary loop was measured at both the cold leg exit from the steam generator (P-13) and at the pressurizer (P-139) and, finally, the pressure drop between taps located in the inlet and outlet channel heads was also recorded (DP-1112).

On the secondary side, both the temperature and pressure of the main feedwater were measured at the inlet to the steam generator (T-2101 and P-2101). The main feedwater flow rate was measured using a venturi together with narrow, middle, and wide range differential pressure transducers (DP-201A), and the outlet temperature and pressure of the feedwater heater was also obtained (T-265 and P-261).

The temperature and pressure of the auxiliary feedwater at the inlet to the model boiler were both measured (T-299, P-299), while the auxiliary feed flow was measured using a venturi (FE-299) and both narrow and wide range differential pressure transducers (DP-299).

Finally, steam pressure measurements were made at the outlet from the steam generator (P-91).

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08

The flow coefficients for the primary flow annubar, low primary flow venturi, and main and auxiliary feedwater flow venturis were derived from calibration tests performed either by the vendors of the flow meters or by Westinghouse.

Cold leg elevation head corrections for all differential pressure and absolute pressure measurements made use of the ambient air temperature recorded by thermocouples T-601, T-602, and T-603 located at various elevations adjacent to the MB-2 model.

3-5 DATA ACQUISITION SYSTEM DESCRIPTION

All of the digital data were acquired using a Data General computer system.

The Data General computer system consisted of the following main frame and peripheral equipment:

Device	Features
CPU	Eclipse S/130 with 128K byte memory and floating point instruction set
Terminal	Keyboard with CRT which displayed up to 24 lines of 80 characters each
Magnetic Tape Unit	9 track, 75 inches per second, 800 bytes per inch density
Disc Drive	10 Megabyte fixed-disc capacity plus 10 megabyte removable-disc capacity with 20 megabyte total disc capacity
Line Printer	180 characters per second, bidirectional

The computer system had the following capabilities:

Max. number of low-level channels:	192 channels capable of accepting analog signals in ranges for ±5 mV up to ±1000 mV. These channels were suitable for thermocouple inputs and other low-level signal inputs.
Max. number of high-level channels:	80 channels capable of accepting ±4.096 volt analog signal inputs. These channels were used mainly for process signals and steam generator pressure and differential pressure data.
Total number of channels:	272 channels (192 low level and 80 high level)
Max. sampling rate(1):	All 272 channels every 0.1 second
Min. sampling rate(1):	All 272 channels every 99.9 seconds
Max. test run time:	99,999 seconds
Max. samples per test:	12,500 samples

---

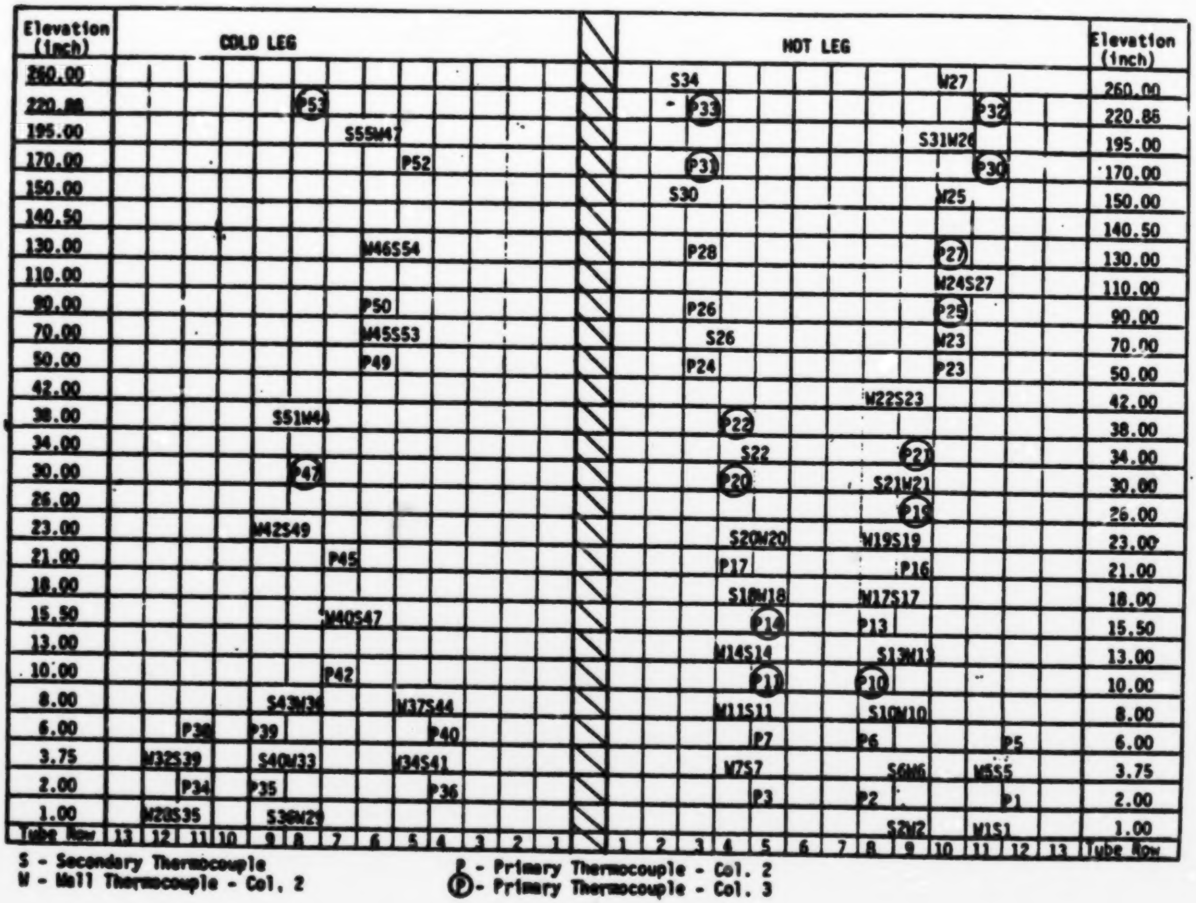
(1) The sampling rate could be changed once during the test run, if desired.

60

3-6. REFERENCES

1. Hochreiter, L. E. et al., PWR FLECHT-SEASET System Effects Natural Circulation and Reflux Condensation Task Plan Report, NUREG/CR-2401 (1983).

61


Elevation (inch)
COLD LEG
HOT LEG
Elevation (inch)
260.00
220.86
195.00
170.00
150.00
140.50
130.00
110.00
90.00
70.00
50.00
42.00
38.00
34.00
30.00
26.00
23.00
21.00
18.00
15.50
13.00
10.00
8.00
6.00
3.75
2.00
1.00
Tube Row
13 12 11 10 9 8 7 6 5 4 3 2 1
1 2 3 4 5 6 7 8 9 10 11 12 13
P53
S55W47
P52
W46S54
P50
W45S53
P49
S51W48
P47
W42S49
P45
W40S47
P42
S43W36
W37S44
P38
P39
P40
W32S39
S40W33
W34S41
P34
P35
P36
W28S35
S36W29
S34
W27
P33
P32
S31W26
P31
P30
S30
W25
P28
P27
W24S27
P26
P25
S26
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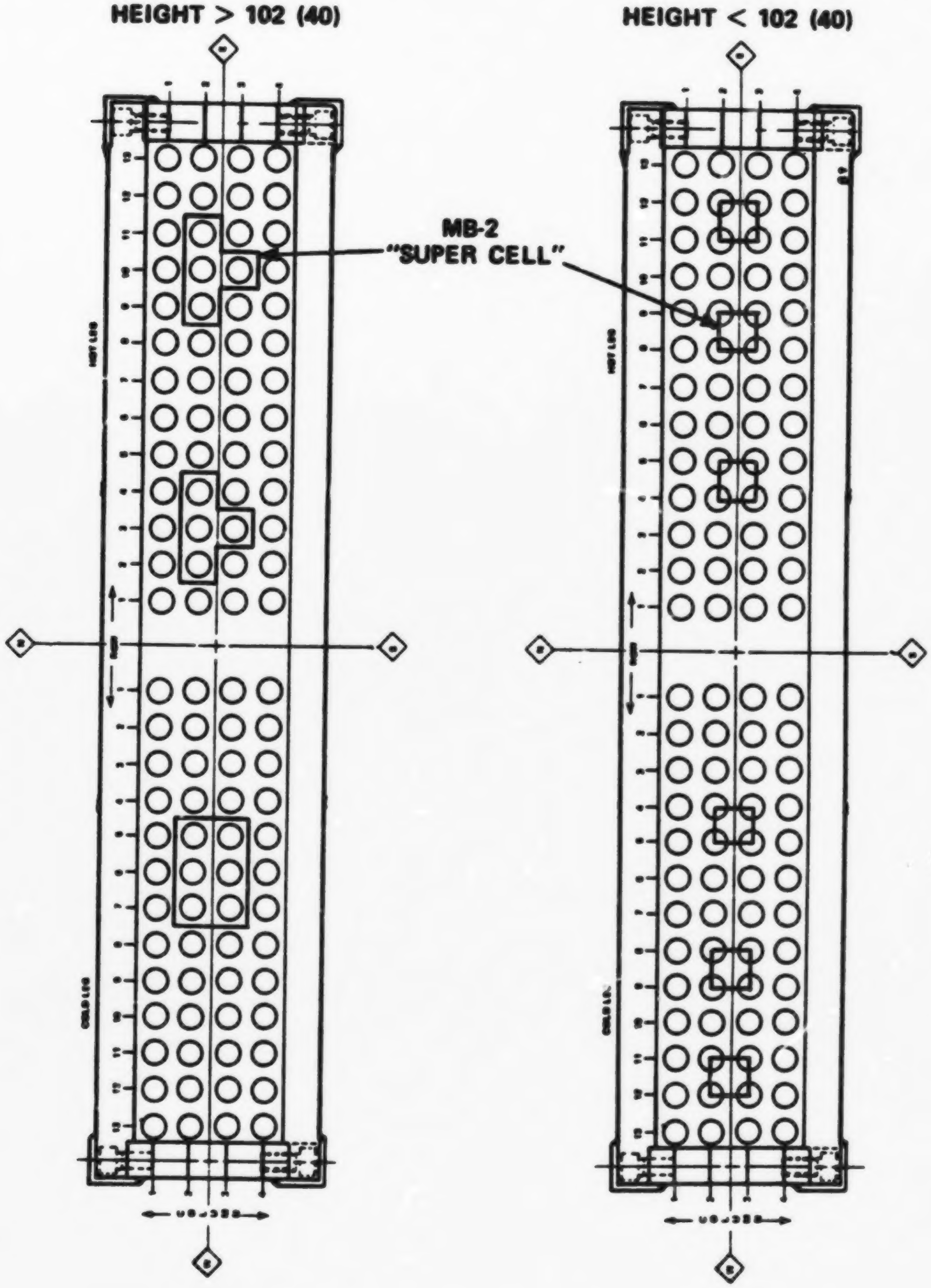
P24
P23
W22S23
P22
S22
P21
P20
S21W21
P19
S20W20
W19S19
P17
P16
S18W18
W17S17
P14
P13
W14S14
S13W13
P11
P10
W11S11
S10W10
P7
P6
P5
W7S7
S6W6
W5S5
P3
P2
P1
S2W2
W1S1
S - Secondary Thermocouple
W - Wall Thermocouple - Col. 2
P - Primary Thermocouple - Col. 2
Ⓟ - Primary Thermocouple - Col. 3

Figure 3-1. Location of MB-2 Tube Bundle Thermocouples

ALL DIMENSIONS IN cm (in.)

8741E-9

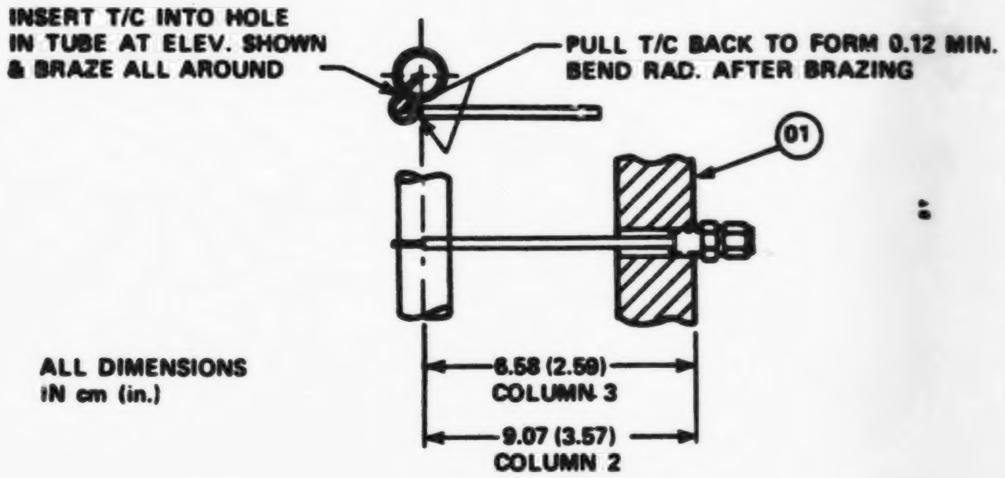

HEIGHT > 102 (40)
HEIGHT < 102 (40)
MB-2
"SUPER CELL"

(B)

(A)

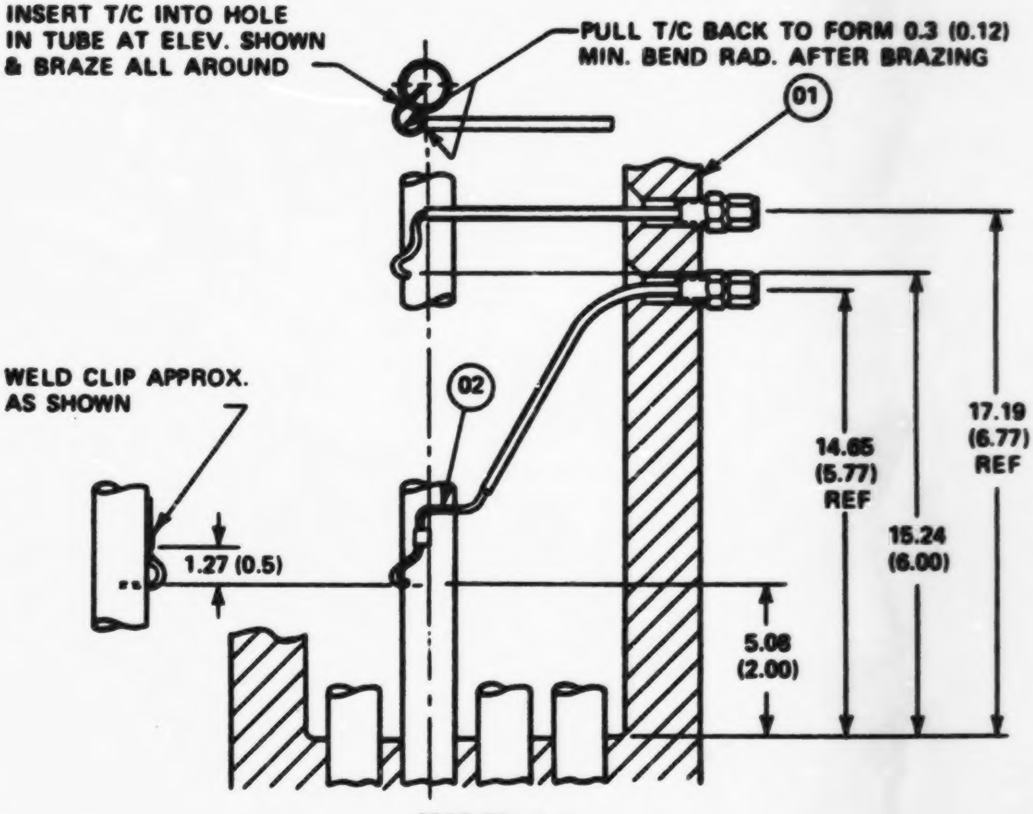
Figure 3-2. MB-2 Bundle Cross-Section and Super Cell Locations

6741E-7


INSERT T/C INTO HOLE
IN TUBE AT ELEV. SHOWN
& BRAZE ALL AROUND
PULL T/C BACK TO FORM 0.12 MIN.
BEND RAD. AFTER BRAZING
01
ALL DIMENSIONS
IN cm (in.)
6.58 (2.59)
COLUMN 3
9.07 (3.57)
COLUMN 2

SECTION B-B

AT HIGHER ELEVATIONS


INSERT T/C INTO HOLE
IN TUBE AT ELEV. SHOWN
& BRAZE ALL AROUND
PULL T/C BACK TO FORM 0.3 (0.12)
MIN. BEND RAD. AFTER BRAZING
01
WELD CLIP APPROX.
AS SHOWN
02
1.27 (0.5)
5.08
(2.00)
14.65
(5.77)
REF
15.24
(6.00)
17.19
(6.77)
REF

SECTION A-A

ELEVATIONS NEAREST THE TUBESHEET

Figure 3-3. MB-2 Primary Thermocouple Configurations

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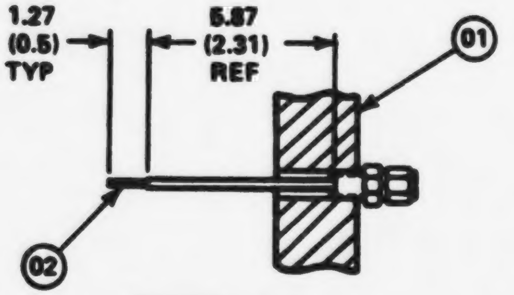
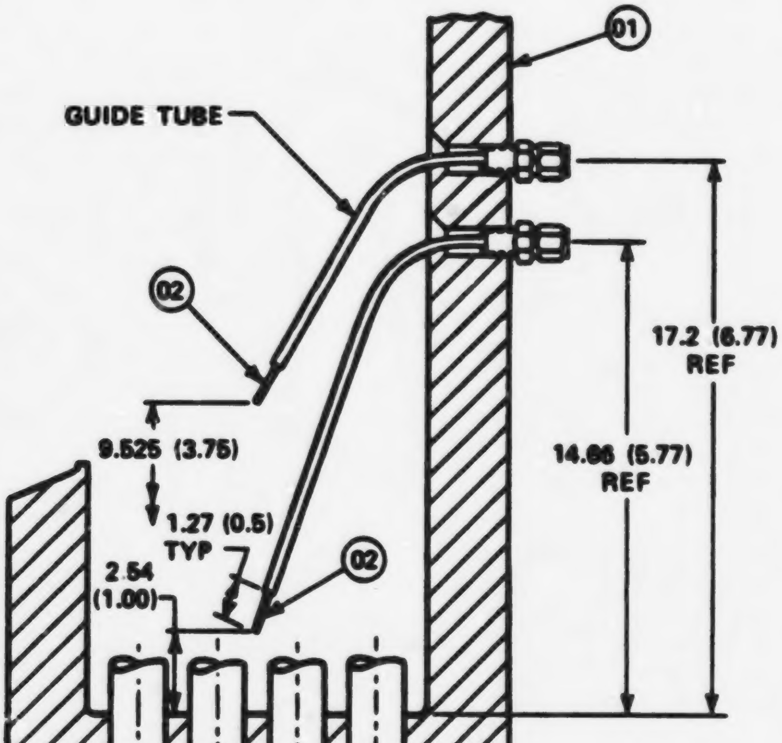
64

6741E-6

ALL DIMENSIONS IN cm (in.)


1.27
(0.5)
TYP
5.87
(2.31)
REF
01
02

SECTION B-B
AT HIGHER ELEVATIONS


01
GUIDE TUBE
02
9.525 (3.75)
1.27 (0.5)
TYP
2.54
(1.00)
02
17.2 (6.77)
REF
14.66 (5.77)
REF

SECTION A-A
ELEVATIONS NEAREST THE TUBESHEET

Figure 3-4. MB-2 Secondary Thermocouple Configurations

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65

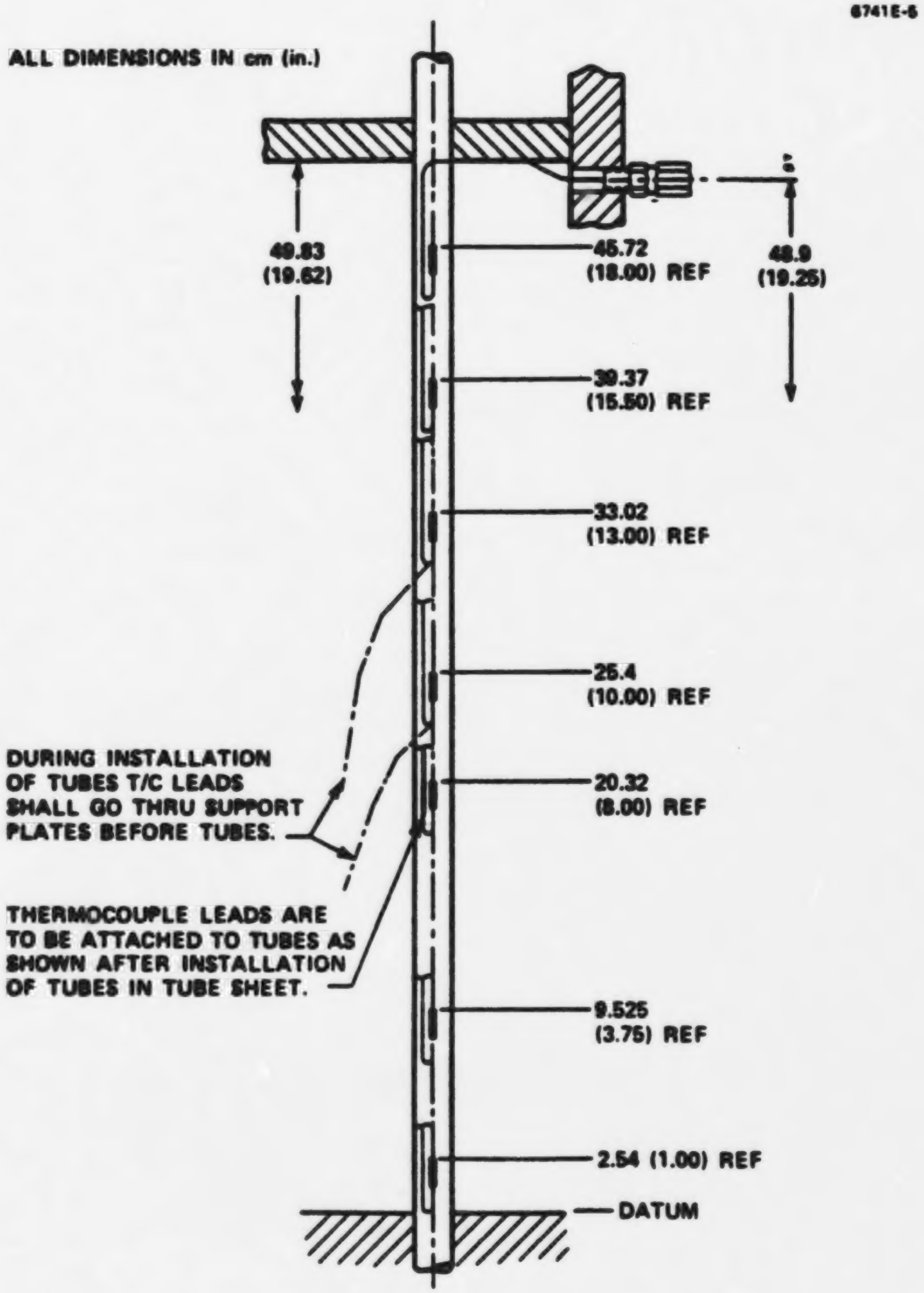
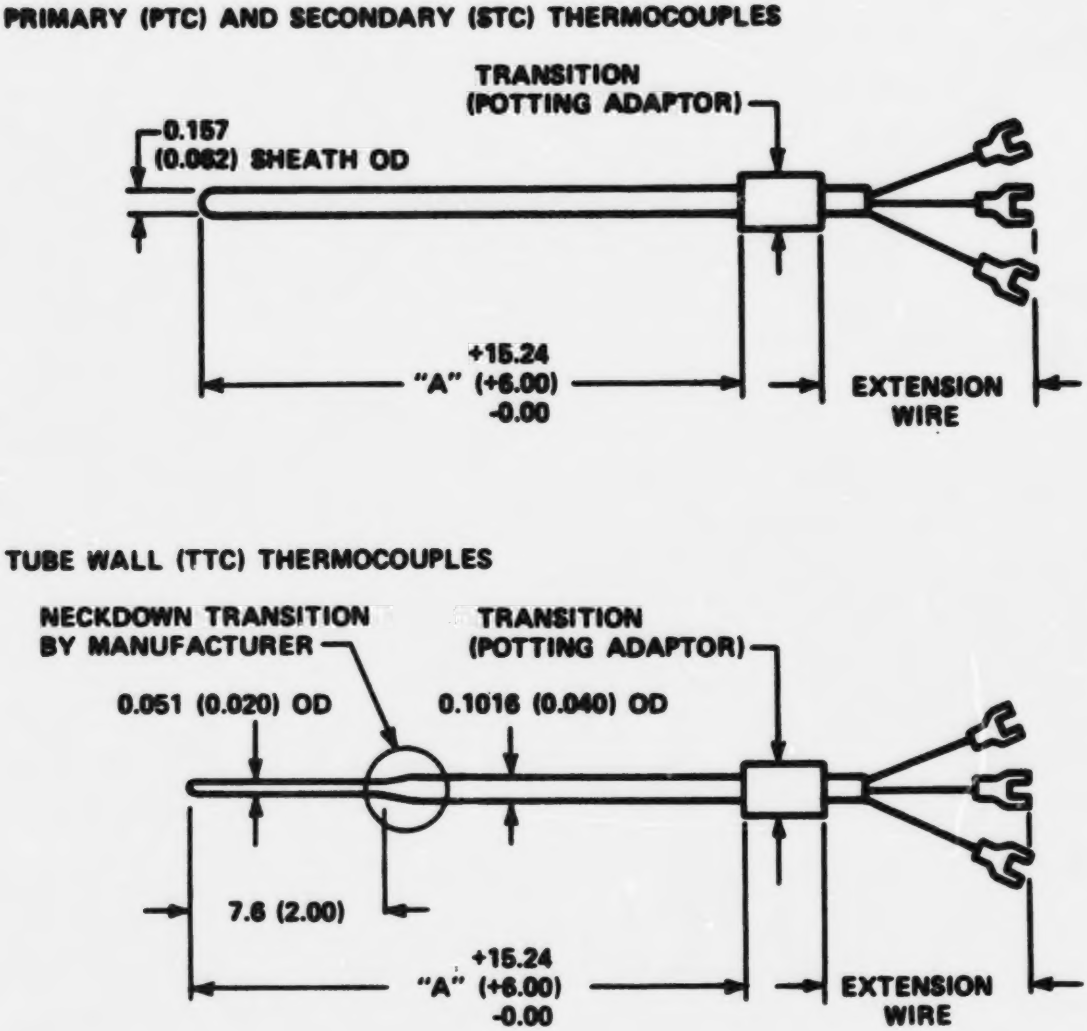

6741E-5
ALL DIMENSIONS IN cm (in.)
49.83
(19.62)
48.9
(19.25)
45.72
(18.00) REF
39.37
(15.50) REF
33.02
(13.00) REF
25.4
(10.00) REF
20.32
(8.00) REF
DURING INSTALLATION
OF TUBES T/C LEADS
SHALL GO THRU SUPPORT
PLATES BEFORE TUBES.
THERMOCOUPLE LEADS ARE
TO BE ATTACHED TO TUBES AS
SHOWN AFTER INSTALLATION
OF TUBES IN TUBE SHEET.
9.525
(3.75) REF
2.54 (1.00) REF
DATUM

Figure 3-5. MB-2 Tube Wall Thermocouple Configurations
(Routing Below the Flow Distribution Baffle)

6741E-8

ALL DIMENSIONS IN cm (in.)



PRIMARY (PTC) AND SECONDARY (STC) THERMOCOUPLES

TUBE WALL (TTC) THERMOCOUPLES

TRANSITION
(POTTING ADAPTOR)
0.157
(0.062) SHEATH OD
+15.24
"A" (+6.00)
-0.00
EXTENSION
WIRE
NECKDOWN TRANSITION
BY MANUFACTURER
TRANSITION
(POTTING ADAPTOR)
0.051 (0.020) OD
0.1016 (0.040) OD
7.6 (2.00)
+15.24
"A" (+6.00)
-0.00
EXTENSION
WIRE

"A" – VARIOUS LENGTHS

Figure 3-6. MB-2 Thermocouple Dimensions

67

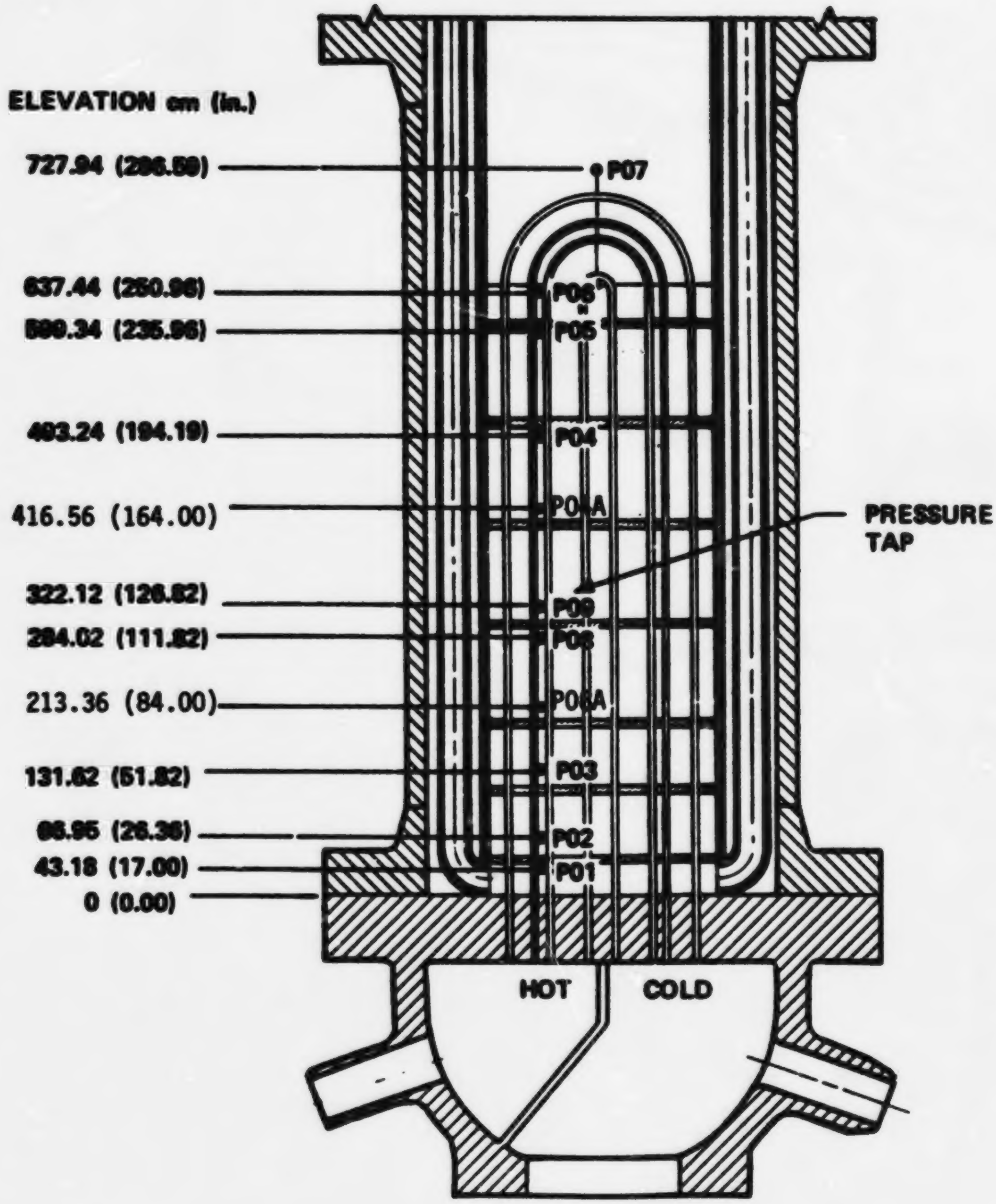

ELEVATION cm (in.)
727.94 (286.59)
P07
637.44 (250.96)
P06
599.34 (235.96)
P05
493.24 (194.19)
P04
416.56 (164.00)
P04A
PRESSURE TAP
322.12 (126.82)
P09
284.02 (111.82)
P08
213.36 (84.00)
P08A
131.62 (51.82)
P03
66.95 (26.36)
P02
43.18 (17.00)
P01
0 (0.00)
HOT
COLD

Figure 3-7. Secondary Side Pressure Taps Within Tube Bundle

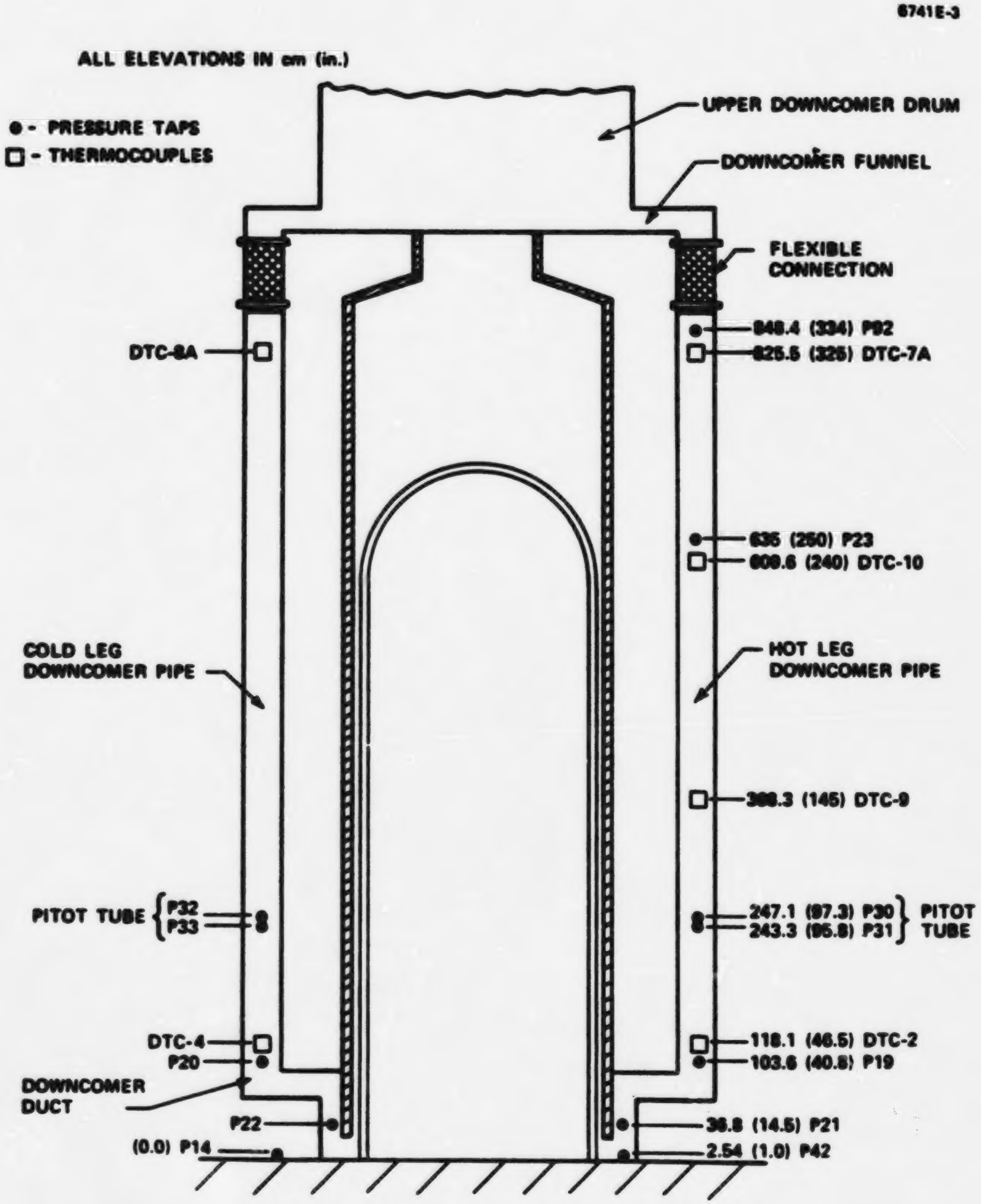

6741E-3
ALL ELEVATIONS IN cm (in.)
● - PRESSURE TAPS
☐ - THERMOCOUPLES
UPPER DOWNCOMER DRUM
DOWNCOMER FUNNEL
FLEXIBLE CONNECTION
848.4 (334) P92
DTC-8A
825.5 (325) DTC-7A
635 (250) P23
609.6 (240) DTC-10
COLD LEG DOWNCOMER PIPE
HOT LEG DOWNCOMER PIPE
368.3 (145) DTC-9
PITOT TUBE
P32
P33
247.1 (97.3) P30
243.3 (95.8) P31
PITOT TUBE
DTC-4
P20
118.1 (46.5) DTC-2
103.6 (40.8) P19
DOWNCOMER DUCT
P22
36.8 (14.5) P21
(0.0) P14
2.54 (1.0) P42

Figure 3-8. Pressure Taps and Thermocouples Within MB-2 Downcomer Pipes

69

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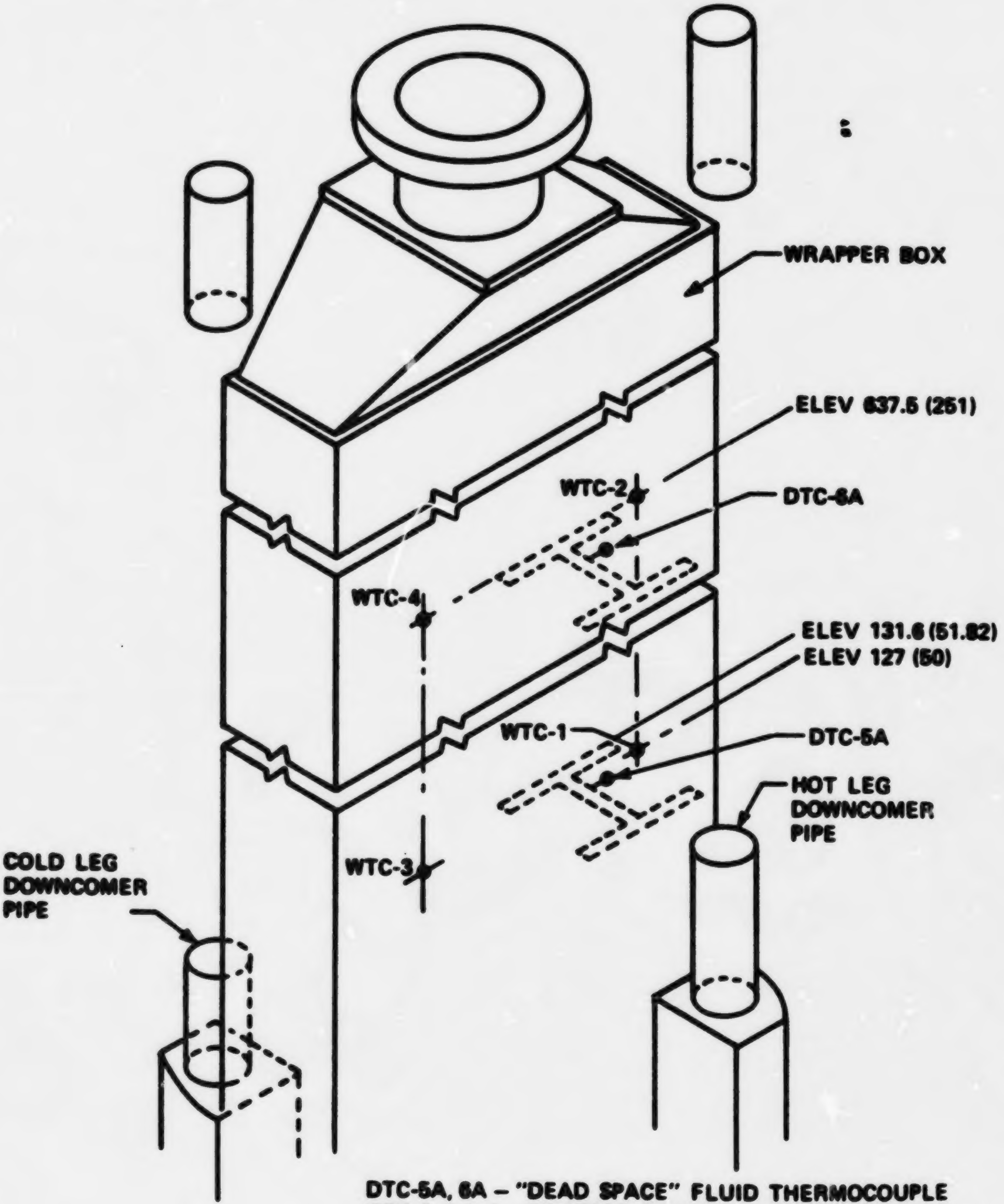
ALL DIMENSIONS IN cm (in.)


WRAPPER BOX
ELEV 637.5 (251)
WTC-2
DTC-6A
WTC-4
ELEV 131.6 (51.82)
ELEV 127 (50)
WTC-1
DTC-5A
HOT LEG DOWNCOMER PIPE
COLD LEG DOWNCOMER PIPE
WTC-3

DTC-5A, 6A – "DEAD SPACE" FLUID THERMOCOUPLE
WTC-1, 2, 3, 4 – WRAPPER BOX WALL THERMOCOUPLE

Figure 3-9. Location of Dead Space and Wrapper Box Wall Thermocouples

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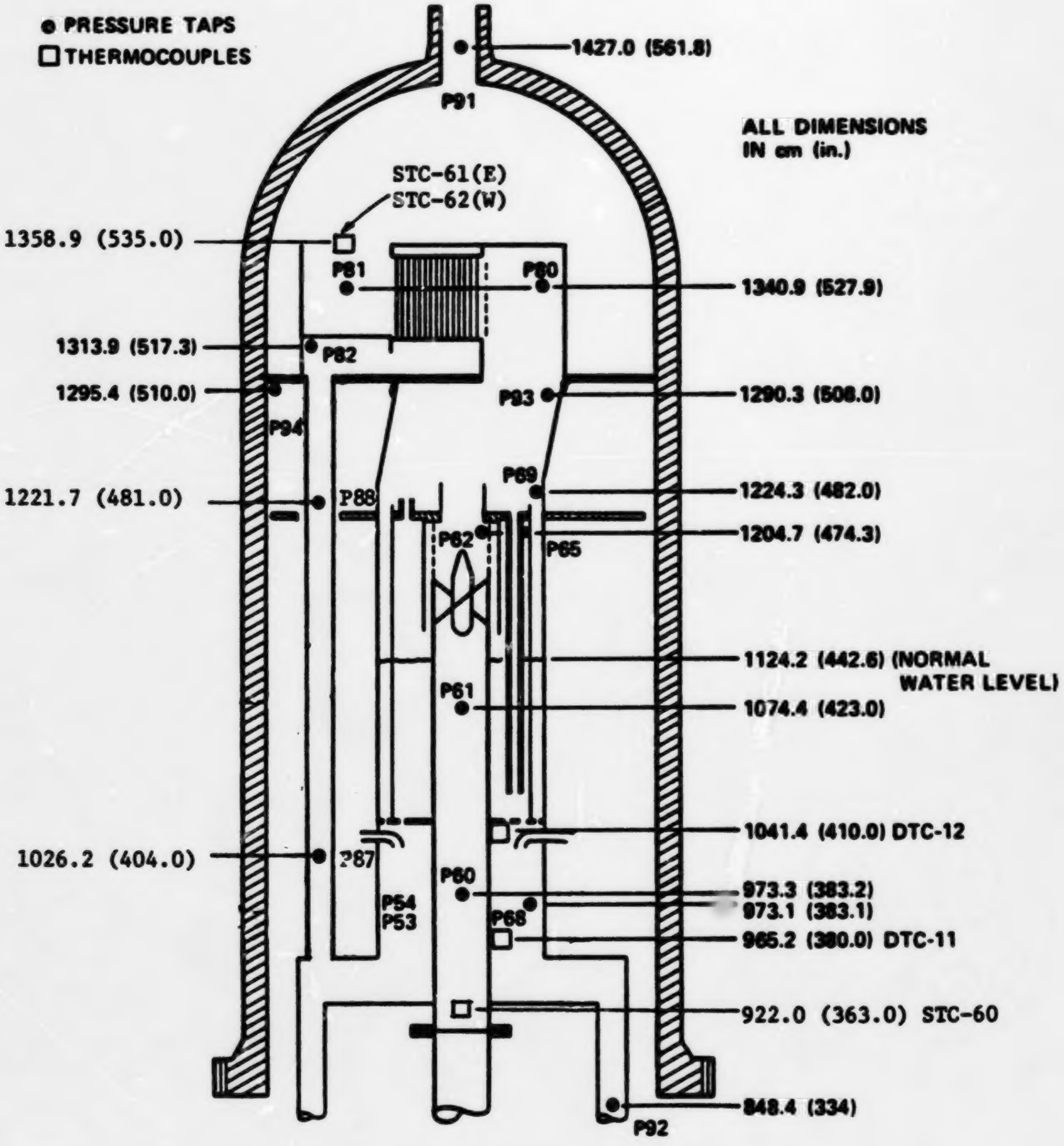
● PRESSURE TAPS
☐ THERMOCOUPLES
1427.0 (561.8)
P91
ALL DIMENSIONS
IN cm (in.)
STC-61(E)
STC-62(W)
1358.9 (535.0)
P81
P80
1340.9 (527.9)
1313.9 (517.3)
P82
1295.4 (510.0)
P94
P93
1290.3 (508.0)
P89
1221.7 (481.0)
P88
1224.3 (482.0)
P62
P65
1204.7 (474.3)
1124.2 (442.6) (NORMAL
WATER LEVEL)
P61
1074.4 (423.0)
1041.4 (410.0) DTC-12
1026.2 (404.0)
P87
P60
P54
P53
P68
973.3 (383.2)
973.1 (383.1)
965.2 (380.0) DTC-11
922.0 (363.0) STC-60
848.4 (334)
P92

Figure 3-10. Location of Pressure Taps and Thermocouples in MB-2 Upper Shell Region (Phase II Tests)

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71

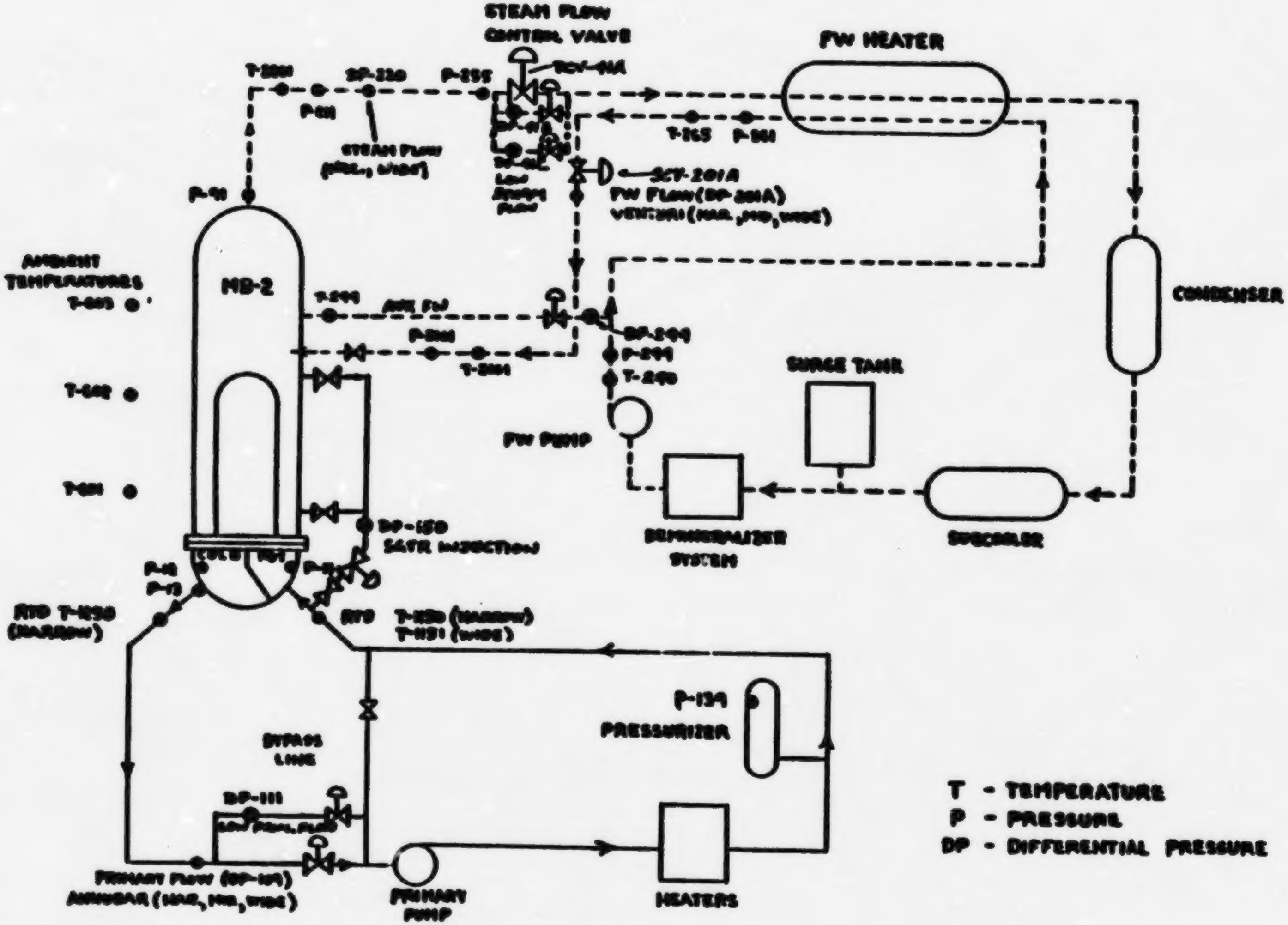
STEAM FLOW
CONTROL VALVE
FW HEATER
SCV-201A
FW FLOW (DP-201A)
VENTURI (NAR.,MID,WIDE)
STEAM FLOW
T-265
P-266
P-255
DP-220
P-91
AMBIENT
TEMPERATURES
MB-2
CONDENSER
SURGE TANK
FW PUMP
DEMINERALIZER
SYSTEM
SUBCOOLER
DP-150
SATR INJECTION
RTD T-1230
(NARROW)
RTD
T-1230 (NARROW)
T-1231 (WIDE)
P-134
PRESSURIZER
BYPASS
LINE
DP-111
PRIMARY FLOW (DP-101)
ANNUBAR (NAR., MID, WIDE)
PRIMARY
PUMP
HEATERS
T - TEMPERATURE
P - PRESSURE
DP - DIFFERENTIAL PRESSURE

Figure 3-11. MB-2 Primary and Secondary Loop Instrumentation
(See Figure 2-12 for Phase II Modifications)

72

SECTION 4

CHEMICAL CONTROL AND INSTRUMENTATION

4-1. ANALYTICAL MEASUREMENTS

For the tests two main types of analytical instruments were available. These were the four conductivity monitors fitted to the sample lines and the atomic absorption spectrophotometer used for batch analysis.

4-1-1. Continuous Monitors

For the continuous monitoring of the relatively concentrated primary and model boiler (S-1 and IKP-4) sample streams each sample line was fitted with Foxboro flow cells, conductivity probes and monitors. Initially, type 910 conductivity probes having cell constants of 1.0 were fitted to each line. These were connected to type 910M temperature compensated conductivity monitors which could operate over three alternative ranges of 0-20, 0-200 and 0-2000 µS/cm. After the initial tests had shown that high steam generator concentrations were required to detect carryover, the S-1 and IKP-4 conductivity probes were replaced by identical models having cell constants of 10; these extended the measurement ranges to 0-2000 µS/cm.

For the SORV condensate sample the conductivities expected could not easily be defined. In principle, they could range from that of almost pure water to that approaching model boiler water, depending on the degree of carryover of both the tracer chemicals and of other constituents of the water. To cover this wide range of possibilities a Foxboro 920M resistivity monitor and 920 conductivity probe of cell constant 0.01 were fitted to this line. While primarily designed for use in ultra pure water, this monitor could be used over ranges of 0-0.2, 0-2 and 0-20 megohm-cm and thus could be used satisfactorily even in solutions having conductivities of approximately 200 µS/cm.

73

At both the start and end of the test series the primary, S-1 and IKP-4 conductivity monitors were calibrated by immersing the probes in solutions of potassium chloride at ambient temperature (approximately 22°C) and at concentrations of 50, 125 and 250 ppm (192, 480 and 960 µS/cm at 25°C). In each case the measured values were found to be approximately 2% lower than the calculated values. The resistivity monitor could not be calibrated as the readings became inaccurate in dilute solution, due to contamination and poor mixing in non-flowing solutions, but a similar level of accuracy is expected.

4-1-2. Batch Analyses

Batch analyses were carried out using a Perkin Elmer 360 Atomic Absorption Spectrophotometer operating as a flame emission spectrophotometer for maximum sensitivity. Due to the number of samples produced in each test, between 70 and 200 per test, the analyses were restricted to two analytical ranges, 0 to 20 ppb and 0 to 1 ppm for both lithium and potassium. The samples collected were either analyzed undiluted or brought into one of the analytical ranges by dilution. Generally a dilution of 1 to 100 was used, but on occassion samples were diluted 1 to 200 or 1 to 1000.

Analytical standards were prepared from standard solutions containing 1000 ppm lithium or potassium (Fisher Certified Reagents, atomic absorption reference standard solutions). These were diluted in grade A volumetric flasks to provide stock solutions containing either 1 or 10 ppm lithium or potassium. The stock solutions were further diluted to provide working standards. Low level standards were prepared daily; the 0.5, 1 and 2 ppb standards from 1 ppm stock solution and the 5, 10 and 20 ppb standards from 10 ppm stock solution. High level standards were prepared only as required. All standards were prepared using micropipettes (Eppendorf Tip Ejector Microliter Pipettes) and with water having a conductivity of 0.06 µS/cm or less. The demineralized water was produced using a Mitco Water Laboratories demineralization unit, which consisted of three sequential mixed bed ion exchange canisters followed by a carbon filter. All standards were stored in 600 ml polystyrene tissue culture bottles (Corning, type 25120), which had been soaked in demineralized water before use.

For each test samples were collected in 70 ml polystyrene tissue culture bottles (Corning, type 25100). These were soaked in demineralized water for at least one day before use; the bottles were not reused. Samples were diluted by the same procedure as was used for standard solutions. Low level samples were analyzed within 2 to 3 hours of sample collection and high level samples within 1 day. Tests showed no significant lossed due to plateout on storage.

In each test a standard calibration graph was prepared. For this the spectrophotometer was set to zero absorbence on blank water and then set to 100% emission using the highest standard solution. During each series of analyses the zero and 100% emission set points were reset every five to ten determinations. The precision of the analytical procedure has been estimated from the individual calibrations carried out for each test. These are given in Table 4-1. For both lithium and potassium the precision was generally of the order of 0.5 to 1.0% emission corresponding to approximately 0.1 to 0.2 ppb over the range 0 to 20 ppb and 5 to 10 ppb over the range 0 to 1 ppm. Throughout the tests the precision of the analysis for lithium was unaffected by rig operation. However, for potassium the precision was, on occassion, affected by the vibration of the building during the test or by air-borne contamination from the sea. Of the tests only the initial test, Test 1, was particularly affected in this way with the practical limit of detection being raised to about 1 ppb.

Throughout the test series other determinands were analyzed by standard analytical methods. Specifically, oxygen, ammonia and hydrazine were analyzed using Chemets analytical test kits, pH measured using standard electrodes and conductivity measured using a flow-through conductivity cell and a conductivity bridge.

4-2. CHEMISTRY CONTROL DURING TRANSIENT TESTS

For each Phase II test a standard method was used to add chemical tracers to the primary loop, the model boiler and the primary makeup tank and to dose the surge tank with hydrazine. With some exceptions, a standard procedure was also used for chemical sampling and monitoring. These general procedures are described below.

75

4-2-1. Loop Chemistries

At startup the primary loop was dosed with a 45% w/w potassium hydroxide solution (Fisher Certified Reagent) to pH 9.0 to 9.5 and with hydrazine to deoxygenate the water. At rig operating temperature the hydrazine decomposed to ammonia, which then built up in the loop as additional hydrazine, was added via the makeup water. Normally, dissolved oxygen levels were low, < 5 ppb, but residual hydrazine levels ranged from 0.01 to 10 ppm with occasional excursions to higher concentrations. Before each test the potassium concentration in the loop was measured and, if necessary, the concentration raised to the target tracer level by adding a further calculated quantity of 45% w/w potassium hydroxide solution.

In each test water from the primary makeup tank was added to the primary loop to replace that injected into the model boiler. The quantity injected varied from test to test, but ranged from approximately 1280 lb (580 kg, Test 5) to approximately 6200 lb (2800 kg, Test 12). This represents from 14% to 72% of the primary loop mass at temperature, approximately 8700 lb (4000 kg, volume 200 cu. ft. or 5663 liters). As the makeup tank normally contained 3 to 5 ppm dissolved oxygen, it was considered essential to add excess hydrazine to the tank before each test; the oxygen would then be consumed as soon as the makeup water entered the primary loop. Generally, the dosing level used was between 9 and 16 ppm hydrazine. For all tests the potassium concentrations were matched to those in the primary loop to avoid rapid changes in concentration during the tests.

The secondary loop was dosed at startup in a similar manner to the primary loop, but here ammonia was used as the alkalysing agent. Again, due to the rapid sequence of tests, it was difficult to maintain a stable loop chemistry. However, normally the loop was maintained with the pH in the range 8.0 to 9.5, with ammonia at < 1 to 5 ppm and hydrazine at 0.01 to 6 ppm. Before each test the dissolved oxygen level was normally < 5 ppb. Immediately before each test the model boiler alone was dosed with lithium hydroxide to give the desired tracer concentration. This was carried out by injecting a concentrated solution, prepared from the anhydrous solid (Fisher purified chemical), into the auxiliary feed line. Initially, the amount of

16

lithium hydroxide required to give the specified tracer concentration was not known, but for later tests a standard dose rate of 2 g anhydrous lithium hydroxide powder for each ppm lithium in the model boiler was found to be satisfactory. During each test water was drawn from the surge tank to replace that lost via the 2% or 8% SORV lines. The quantities varied from test to test, but on occasion the entire contents of the tank (4000 to 5000 gallons, 33000 to 42000 lbm water) were used during a test. To ensure that no damage to the model boiler occurred, the class A demineralized water in the surge tank was dosed with excess hydrazine before each test and, when required, on refilling during the tests. It was then expected that the oxygen would be consumed rapidly as the heated water passed down the internal downcomer of the model boiler. In general, the surge tank contained from 3 to 5 ppm dissolved oxygen and from 4 to 12 ppm hydrazine before any test. With the exception of Test 5 the dissolved oxygen concentrations for the sample S-1 on completion of the tests were typically 60 to 200 ppb. In Test 5 the model boiler temperature was so low that the oxygen did not react rapidly with hydrazine. As a result, the samples collected in this test were a pale yellow color due to the presence of ferric ions. However, as the major corrosion risk to the model boiler was expected to be stress corrosion cracking of the Inconel 600 tubing, and as rapid attack only occurs at higher temperatures, no additional risk was anticipated.

On completion of each test the chemical tracers in the model boiler were normally removed by a series of fill and blowdown cycles. Normally, these were monitored by following the S-1 sample conductivity. Usually 3 to 5 blowdowns were sufficient to reduce the levels in the boiler to an acceptable potassium concentration (about 2 ppm) and conductivity (30 μS/cm).

4-2-2. Sampling and Monitoring

For any individual test the sample lines, conductivity monitors and recorders were normally setup one to two hours before the test commenced. Typically, the S-1, IKP-4 and primary samples were adjusted to give a flow rate of 60 to 80 ml/min, while the SORV condensate sample was allowed to flow at its maximum rate. For most tests the SORV condensate line gave a constant flow, but for Tests 3, 4, 5 and 14 it was necessary to increase the backpressure in the

77

line from the SORV condenser to the SORV tank (accomplished by substituting a 3/8-inch O.D. line for the normal 3/4-inch O.D. line) in order to ensure a stable flow. In most tests the flow rates for the S-1, IKP-4 and primary samples decreased slowly with time. For all tests the actual flow rates were determined periodically using a measuring cylinder and stop watch.

For each test, samples and thermal-hydraulic data were collected for a fixed period, usually 30 minutes, before the SGTR was initiated and for a similar period after the SGTR had been halted. For most tests primary samples were normally collected at 30 minute intervals, while the S-1, IKP-4 and SORV condensate samples were collected at 15 minute intervals. Samples were collected at more frequent intervals, normally every 5 minutes, at the start of the SGTR injection or when there were rapid level changes, or other rapid changes in conditions, within the model boiler. In all cases the samples were collected in the presoaked tissue culture bottles, having first rinsed the bottles with the sample. Generally, the S-1, IKP-4 and primary samples were collected over a period of about 1 minute, commencing about 0.5 minutes before the nominal time of collection. The SORV condensate sample was normally collected over a period of 5 to 10 seconds at the indicated collection time.

78

TABLE 4-1

PRECISION OF ANALYSES FOR LITHIUM AND POTASSIUM

	Lithium			Potassium		
Concentration (p.p.b.)	Mean Emission (%)	Standard Deviation		Mean Emission (%)	Standard Deviation	
		Emission (%)	Concentration (ppb)		Emission (%)	Concentration (ppb)
0	0	-	-	0	-	-
0.5	3.05	0.69	0.14	2.93	0.53	0.11
1.0	6.00	1.15	0.23	5.43	0.53	0.11
2.0	10.90	0.57	0.11	10.93	0.84	0.17
5.0	25.90	0.57	0.11	25.14	1.46	0.29
10.0	50.90	1.20	0.24	50.14	0.38	0.08
20.0	100	-	-	100	-	-
0	0	-	-	0	-	-
50	5.06	0.18	1.8	5.28	0.44	4.4
100	10.56	0.50	5.0	10.11	0.60	6.0
200	20.75	0.71	7.1	21.56	2.36	23.6
500	51.00	1.20	12.0	51.00	1.22	12.2
1000	100	-	-	100	-	-

Notes: (a) based on approximately 10 calibration graphs for each range.

(b) limit of detection estimated as 0.2 to 0.3 ppb (2.3σ) for 0 to 20 ppb range.

SECTION 5

TEST PERFORMANCE

Test 1 - 2% SORV Flow with SGTR at Bottom of Tube Bundle (T-1952)

This was the initial shakedown steady-state test with a 2% SORV flow and with SGTR injection at the bottom of the tube bundle. The conditions and SORV flow rate chosen were those that would exist at an early stage in an overall SGTR/SORV transient, before isolation of the faulted steam generator and when all four steam generators would be discharging through the stuck-open safety relief valve. The test objective was to assess the scrubbing effect of the tube bundle and upper generator internals on the high velocity SGTR discharge without flashing, and to demonstrate the capabilities of the chemical monitoring system. The target initial steady-state plant conditions were as follows:

Plant Parameter	Desired Value
Primary pressure	1850 psia (127.6 bar)
Primary T_{hot}	560°F (293°C)
Primary flow rate	As required to maintain desired secondary pressure
Secondary pressure	1080 psia (74.5 bar)
Saturation temperature	554°F (290°C)
Water level (from top of tubesheet)	442.5 in. (11.24 m)
SORV flow	2%

To achieve these conditions, the primary flow rate was increased to the maximum attainable (91 lbm/sec) and then T_{hot} was raised to 565°F (296°C) to achieve the specified steam pressure of 1080 psia. Before the test, the model boiler void space was drained, but steam could still pass from the steam dome into the void space. Periodically, the void space drain valve was opened to drain off any additional accumulated condensate. However, during data collection the void space drain valve was kept closed to prevent excessive steaming through the void space.

Before the SGTR phase of the test, the SGTR line was warmed up for a minimum of 5 minutes and was then lined up with the bottom SGTR element. During this period, water level was maintained using both the main feedwater line, maintained with HCV-222 cracked 1/4 turn open, and the auxiliary feedwater line, controlled via FCV-299. The SGTR flow was initiated 1 minute after commencing data collection. As the steam generator water level rose on initiating the SGTR flow, the auxiliary feedwater was throttled in an attempt to maintain the normal water level (442.5 in.). After 2 minutes the auxiliary feed flow was halted, but the water level still continued to increase slowly since the SGTR flow was greater than the 2% SORV flow. The SGTR flow was terminated 119 minutes after initiation (t = 120 minutes) and the auxiliary feedwater was reinitiated to maintain the water level at its final level (470 in.). Plant test conditions were maintained for another 30 minutes to allow the model boiler chemistry to stabilize.

Figures 5-1 to 5-14 illustrate the performance of relevant thermal-hydraulic parameters during the test. Chemical samples were collected both before and during the SGTR phase of the test. During the test, it was found that the use of the main feedwater line introduced particulate matter into the model boiler which in turn affected the sample line flows. The presence of these particulates did not appear to affect the carryover results. In this test primary loop water lost via the SGTR was replaced by makeup tank water injected into the primary loop by the main charging pump. This pump, run at full speed, caused general vibration of the loop buildings and, in particular, dislodged dust containing potassium in the analytical laboratory. In consequence, the limit of detection for potassium was raised for this particular test. In other tests the second charging pump was used, together with the main charging pump run at reduced speed. The chemistry results are summarized in Tables 5-1 and 5-2 and are shown in Figures 5-15 and 5-16. They are described in detail below.

Prior to the test, the potassium concentration in the primary loop was increased from its pretest value of approximately 5 ppm to 50 ppm. Attempts to achieve an identical concentration in the makeup tank were unsuccessful and this tank contained 77 ppm potassium at the start of the test. As a result, the concentration in the primary loop increased to 54 ppm during the test. This rise is consistent with the amount added from the makeup tank (4176 lbm into a loop mass of about 8700 lbm, i.e., 48%). In contrast with the rise in potassium concentrations, the lithium concentration in the primary loop fell from approximately 3 ppb to 2 ppb during the test. Again, this is consistent with the mass added, assuming that the makeup tank contained no lithium.

Prior to the test, the tracer concentration in the model boiler was 34 ppm lithium, a concentration added for an earlier test in the shakedown program. A further 10 g lithium hydroxide was added raising the tracer concentration to 40 ppm. Equilibration following this addition was rapid, about 10 minutes; thereafter both the conductivity and concentration were essentially constant until the SGTR commenced. Following the start of the SGTR both the conductivity and the potassium concentration rose at an almost linear rate to reach a maximum about 15 minutes after the break had been terminated. From the results the maximum potassium concentration is estimated to be 240 ppm. Over this period, the lithium concentration fell to 34 ppm. This decrease is again believed to be due mainly to dilution on raising level, rather than to sample losses. The latter are estimated at approximately 6% of the initial inventory compared with an overall 15% decrease in concentration.

When allowance is made for the different sample line delays, the results obtained for the S-1 and IKP-4 samples were found to be virtually identical. This is shown in Figure 5-16, the sample lines being corrected for delays of about 1.3 and 8.5 minutes respectively. The agreement suggests that good mixing occurs throughout the model boiler and that both sample points were taking representative samples.

During the test, the pH of the water in the model boiler was found to be low, about pH 9.5 rather than pH 10.8. It is believed that the low pH was caused by acidic impurities in the model boiler water, similar problems were encountered in a number of later tests.

Throughout the test very low levels of both lithium and potassium were detected in the SORV condensate. In both cases the levels were at, or very close to, the detection limits for the two tracers used. Based on the limits of detection for this test (taken as 0.2 ppb lithium and 1 ppm potassium) and on the maximum concentrations in the model boiler (40 ppm lithium and 240 ppm potassium), carryover is estimated to be $\leq 0.0005\%$ and $\leq 0.0004\%$, respectively. The resistivity of the SORV condensate was again low throughout the test and showed a marked change to even lower values during the SGTR. Both before and after the SGTR, the measured resistivity was approximately 0.1 MΩ cm (≅ 10 μS/cm), while during the SGTR it fell to 0.03 to 0.05 MΩ cm (20 to 33 μS/cm). This type of behavior was observed in all SGTR tests and is believed to be due to the differing concentrations of volatile species, mainly ammonia, in the surge tank water and primary loop water. Assuming that the resistivity is due to ammonia, the surge tank water injected about 2 ppm and the primary loop 6 to 10 ppm ammonia into the condensate.

Test 2 - 8% SORV Flow with SGTR at Top of Tube Bundle and Low S/G Water Level (T-1958)

This was designed as a diagnostic test to be carried out under plant conditions that would favor enhanced moisture carryover and/or primary coolant bypassing. The test conditions were generally similar to those established in the previous test (T-1957), but with the water level reduced, as it was hoped that a top SGTR break jetting straight up under these conditions would give significant primary coolant bypassing. The initial steady-state conditions for the test were as follows:

Plant Parameter	Desired Value
Primary pressure	1850 psia (127.6 bar)
Primary T_{hot}	574°F (301°C)
Primary flow rate	48 lbm/sec (21.8 kg/s)
Secondary pressure	1015 psia (70 bar)
Saturation temperature	547°F (286°C)
Water level	240 in. (6.1 m)
SORV flow	8%

Throughout the test the water level was maintained by introducing feedwater via both the auxiliary and main feedwater lines. These were controlled using valves FCV-299 and HCV-222, respectively. Before the test, the model boiler void space was drained, but steam could still pass from the steam dome into the void space. During data collection, the void space drain valve was kept closed to prevent excessive steaming through the void. Before initiating the SGTR flow, the SGTR line was warmed up for at least 5 minutes, it was then lined up with the upper break element and the SGTR initiated.

On initiating the SGTR flow, valve HCV-222 in the main feed line was closed, but this caused a rapid drop in water level. Accordingly, this valve was reopened after a few seconds and water level was recovered and then controlled at about 250 in. After 99 minutes (69 minutes after initiating the SGTR flow), the auxiliary feed flow was halted to allow the water level to boil down to approximately 200 in., so that the upper SGTR break element was further exposed. This level was maintained for approximately 40 minutes after which the level was raised to normal water level, 442 in. The SGTR flow was halted after 165 minutes. In this test, data were collected for a period of 30 minutes before the SGTR, for the 135 minute period of the SGTR and for a further period of 30 minutes after the SGTR.

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84

Figures 5-17 to 5-31 illustrate the performance of the relevant thermal-hydraulic parameters during the test. Chemical samples were collected throughout the test; the results obtained on these samples are summarized in Tables 5-3 and 5-4 and are shown in Figures 5-32 and 5-33. They are described in detail below.

Before the test, the potassium concentration in the primary loop was raised to approximately 54 ppm. Once again, the makeup tank concentration was not exactly matched to this value, the level being 48 ppm potassium, so that the primary loop concentration fell as the SGTR proceeded. As in the earlier test, the lithium concentration in the primary loop water was low, 1.7 ppb, but this also fell during the test as uncontaminated water from the makeup tank was added to the primary loop.

Prior to the test, the tracer concentration in the model boiler was 1 ppm lithium. This was increased to a calculated level of 81 ppm lithium by the injection of 60 g lithium hydroxide (see Section 7-2). As the test proceeded, the measured lithium concentrations varied significantly. Generally, these changes in concentration mirrored the changes in water level that were also occurring, but there was also an underlying trend towards reduced concentrations due to sample line losses. The major changes in concentration observed were the increases that occurred when the water level fell at the start of the SGTR and again after 99 minutes, and the fall in concentration when the water level was raised at the end of the test.

Following the start of the SGTR and over the period when the water level was maintained at about 250 in., both the conductivity and the potassium concentration rose at an approximately linear rate. However, the conductivity record also showed smaller cyclic variations (Figure 5-32) which were due to changes in water level within the model boiler. Similar, but larger changes in both the conductivity and potassium concentration, also occurred when the water level was allowed to boil down to 190 in. and when, subsequently, the water level was raised to 440 in.

85

Even when allowance is made for the differences in sample line delays, the results for the S-1 and IKP-4 sample lines can be seen to differ significantly, except for the period at the end of the test when the water level had returned to normal (Figure 5-33). In general, this behavior was not unexpected, as the S-1 sample point at least should have been uncovered when the downcomer water level fell below 425 in. However, mass balance considerations (Section 7-2) and thermocouple data show that the IKP-4 sample take-off point also lay in a region where two-phase conditions existed. The observed differences merely reflect the different levels of voidage which existed at the two sample points; a difference which became more pronounced as water level was reduced further.

For most of the test, very low levels of both lithium and potassium were detected in the SORV condensate. This includes the initial period of steady-state operation and the SGTR phase at about 250 in. water level, when carryover was barely detectable, and the SGTR phase at about 200 in. water level and above. During the latter phase, carryover tended to be at a significantly higher level, 0.2 to 0.65 ppb lithium and 0.3 to 12.5 ppb potassium. Based on the limit of detection of the analytical methods (0.2 ppb lithium and potassium) and the maximum calculated concentrations in the model boiler (81 ppm lithium and 241 ppm potassium), the carryover at a water level of 250 in. is estimated to be < 0.0005% and < 0.00008%, respectively. At 200 in. water level the carryover, based on the measured levels given above and on model boiler water concentrations of 97 ppm lithium and 461 ppm potassium, was 0.0005% lithium and 0.00007 to 0.00008% potassium. In neither period was there any evidence for selective bypassing of the primary coolant.

On three occasions, higher levels of carryover were seen. These were during two periods when conditions were changing rapidly (at the start of the SGTR and when level was reduced from 250 in. to 200 in.), and on one occasion during the SGTR phase at 200 in. In the latter case, only the potassium level had increased and this sample may have been contaminated, but during the remaining periods the concentrations of both tracers were increased suggesting a real effect. Estimates of the releases during these transients are given in Section 7-3.

As in the previous test, the resistivity of the SORV condensate was low throughout the test; 0.2 to 0.3 MΩ cm (≡ 3.3 to 5 μS/cm) before and after the SGTR and 0.05 to 0.09 MΩm (11 to 20 μS/cm) during the SGTR. Assuming that this is due to ammonia, the surge tank injected 0.3 to 0.6 ppm and the primary loop 2 to 6 ppm ammonia into the condensate.

Test 3 - 8% SORV Flow with SGTR at Bottom of Tube Bundle (T-1970)

This was a steady-state test at reduced pressure, with an 8% SORV flow and with SGTR injection at the bottom of the tube bundle. These conditions correspond to an intermediate stage in the overall SGTR/SORV transient, following the isolation of the faulted steam generator. The specific test conditions were chosen to asses the effect of a flashing SGTR flow on primary coolant bypassing. The target initial steady-state conditions were as follows:

Plant Parameter	Desired Value
Primary pressure	557 psia (38.4 bar)
Primary T_{hot}	427°F (219°C)
Primary flow rate	As required to maintain desired secondary pressure
Secondary pressure	287 psia (19.8 bar)
Saturation temperature	413°F (212°C)
Water level	442.5 in. (11.24 m)
SORV flow	8%

In this test, auxiliary flow was supplied to the model boiler by the auxiliary feedwater line, but with a small additional flow via a leaking valve in the main feedwater line. The leak rate was estimated to be approximately 450 to 600 lbm/hr and was due to the large pressure differential between the feedwater pump discharge (about 1500 psig) and the model boiler at its operating pressure. Before the test, the model boiler void space was drained periodically, but steam could still pass from the steam dome into the void space. During data collection, the void space drain valve was kept closed to prevent excessive steaming through the void.

Before the SGTR phase of the test, the SGTR line was warmed up for at least 5 minutes and it was then lined up with the bottom SGTR break element. On initiating the SGTR flow, the model boiler water level rose sharply. This was counteracted by isolating the main feedwater line and by throttling the auxiliary feedwater flow first to reduce and then to control the water level. On halting the SGTR flow after 120 minutes (at t = 150 minutes), the feedwater flow was provided by both the auxiliary feedwater line and the low flow bypass line to the main feedwater line. Plant conditions were then maintained for another 30 minutes to allow the model boiler chemistry to stabilize.

Figures 5-34 to 5-42 illustrate the performance of the relevant thermal-hydraulic parameters during the test. Chemical samples were collected throughout the tests. The results for these are summarized in Tables 5-5 and 5-6 and are shown in Figures 5-43 and 5-44. The results are described below.

For the test, the primary loop and makeup tank had similar potassium concentrations, 40-41 ppm, and as a result there was little change during the SGTR injection. However, as in other tests the lithium concentration fell from 7 ppb to about 4 ppb during the test. While this occurred in all tests, lithium levels often increased significantly during subsequent loop operations between tests. This was probably due to contamination of the primary loop with model boiler water, but the pathway and conditions under which it occurred could not be identified. In this test, which followed the 100% power moisture carryover test, the highest levels of lithium contamination were observed.

Before starting the test, the model boiler was dosed with 84 g lithium hydroxide to give a concentration of 42 ppm lithium. Over the entire test the concentration fell to about 41 ppm, this is consistent with the sampling losses of 5% and with the absence of any significant change in level. Prior to the SGTR, the conductivity fell even though the lithium concentration remained constant. The reason for this is not known, but probably it reflects changes in the concentrations of ammonia and hydrazine in the surge tank water. During the SGTR phase of the test, the potassium concentration increased linearly to reach a maximum of approximately 80 ppm potassium. Again, as in Test 1, and allowing for sample line delays, the results for the S-1 and IKP-4 sample lines were virtually superimposable except during the subsequent blowdown of the model boiler, Figure 5-44.

The behavior of the SORV condensate was similar to that seen in Test 1. In this case no lithium was detected at any stage in the test, while generally no potassium was detected. On the three occasions when potassium was seen, it is believed that it was due to adventitious contamination. Based on the limit of detection of 0.2 ppb for both elements, upper limits for carryover are $\leq$ 0.0005% (lithium) and $\leq$ 0.00025% (potassium).

In this test the observed changes in resistivity were similar to those seen in all other tests, but at somewhat lower values. Assuming that the resistivity is due to ammonia, then surge tank water produced a concentration in the SORV condensate of 2 to 3.5 ppm (0.06 to 0.9 MΩ cm), while the primary loop water gave about 150 ppm ammonia (0.007 MΩ cm).

Test 4 - 10% SORV Flow with SGTR at Bottom of Tube Bundle (T-1982)

This was a repeat of the bottom break steady-state Test 3, but with the SORV flow rate increased to 10%, the secondary side pressure increased from 287 psia to 305 psia and T_{hot} increased from 427°F to 470°F. These revised conditions were chosen to promote flashing at the SGTR break location and to provide a more representative SORV flow rate. The target initial steady-state conditions are as follows:

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89

Plant Parameter	Desired Value
Primary pressure	557 psia (38.4 bar)
Primary T_{hot}	470°F (243°C)
Primary flow rate	As required to maintain desired secondary pressure
Secondary pressure	305 psia (21 bar)
Saturation temperature	419°F (215°C)
Water level	442.5 in. (11.24 m)
SORV flow	10%

The test was carried out using a procedure essentially identical to that described for Test 3 (T-1970), but with feedwater supplied via the auxiliary feedwater line and the main feedwater line. As before, the void space was drained periodically before the test, the void space drain valve kept closed during the test to prevent excessive steaming through the void space and the SGTR line warmed up before the SGTR flow was indicated. During the SGTR injection, feedwater flow was throttled to maintain water level.

Figures 5-45 to 5-55 illustrate the performance of the relevant thermal-hydraulic parameters during the test. The results for the chemical samples collected during the test are summarized in Tables 5-7 and 5-8 and are shown in Figures 5-56 and 5-57. The results are described below.

For this test, the concentrations of both potassium and lithium in the primary loop fell during the test. Again, this was due to a mismatch between the primary loop and the makeup tank, in this case the makeup tank containing less of both elements. For potassium, the measured concentrations were, primary loop 47 ppm and makeup tank 40 ppm.

Before starting the test, the model boiler was dosed with 85 g lithium hydroxide which equilibrated over 10 minutes to give a concentration of 42 ppm lithium. Prior to the SGTR, both the conductivity and concentration remained constant. During the SGTR injection, the potassium concentration again rose at a constant rate to a maximum of 88 ppm, but in this case the lithium concentration fell slightly to 40 ppm. The latter can be entirely accounted for by the sampling line losses, estimated at 5.2% of the initial inventory, and is consistent with the absence of any dilution due to a level change. Once again, as in other tests at normal water level, the observed concentrations and conductivities for samples S-1 and IKP-4 can be superimposed when allowance is made for the different sample line delays.

The behavior of the SORV condensate was also similar to that observed in other tests. In this case, no detectable carryover of lithium was observed except at the start of the SGTR, while small quantities only of potassium, at or close to the limit of detection, were seen. Although any carryover is poorly resolved, comparison with the repeat test with the dryer bypassed, Test 14 (T-2067), possibly suggests that there was a small peak in carryover at the start of the SGTR injection followed by a slightly increased level of carryover. If the results are due to carryover alone, then the maximum level during the bulk of the SGTR flow, based on the limit of detection of 0.2 ppb lithium or potassium, was $\leq$ 0.0005% (lithium) and $\leq$ 0.0002% (potassium). If the potassium results were due to bypassing alone, the upper limit for bypassing is estimated to be 0.0007 to 0.0008%. An estimate of the transient released at the start of the SGTR injection is given in Section 7-3.

The resistivity of the SORV condensate again showed a clear change during the SGTR. Based on the resistivity levels, the ammonia derived from the contents of surge tank water is estimated to be 0.7 to 0.8 ppm ammonia and that from primary loop water about 70 ppm ammonia. It is probable that the higher value for the primary loop water compared with other tests is due to thermal decomposition of the hydrazine introduced in makeup tank water during the preceding test in chronological order, Test 8, and in normal operation to maintain a residual hydrazine concentration.

Test 5 - 8% SORV Flow with SGTR at Bottom of Tube Bundle (T-1972)

This was a steady-state test at low pressure, with an 8% SORV flow and with SGTR injection at the bottom of the tube bundle. These conditions correspond to a late stage in the overall SGTR/SORV transient. The specific test conditions were chosen to assess the effect of a low velocity non-flashing SGTR discharge. The target initial steady-state conditions were as follows:

Plant Parameter	Desired Value
Primary pressure	170 psia (11.7 bar)
Primary T_{hot}	320°F (160°C)
Primary flow rate	As required to maintain desired secondary pressure
Secondary pressure	85 psia (5.9 bar)
Saturation temperature	316°F (158°C)
Water level	442.5 in. (11.24 m)
SORV flow	8%

For this test, auxiliary feedwater was supplied by the auxiliary feedline alone. Before the test the model boiler void space was drained, but steam could still pass from the steam dome into the void space. During data collection, the void space drain valve was kept closed to prevent excessive steaming through the void.

Before the SGTR phase of the test, the SGTR line was warmed up for at least 5 minutes and it was then lined up with the bottom SGTR break element. On initiating the SGTR flow, the model boiler water level began to rise. Even though the auxiliary feedwater was halted, the level continued to rise. After

100 minutes of SGTR flow, the level exceeded the range covered by the normal narrow range level instrumentation. After halting the SGTR flow, plant conditions were maintained for a further 30 minutes to allow the model boiler chemistry to stabilize.

Figures 5-58 to 5-66 illustrate the performance of the relevant thermal-hydraulic parameters. The results for the chemical samples collected during this test are summarized in Tables 5-9 and 5-10 and shown in Figures 5-67 and 5-68; they are discussed in detail below.

In this test, the composition of the primary loop did not change greatly, due mainly to the reduced SGTR flow under these conditions, resulting in ~ 14% replacement of the loop contents. Thus, even though the makeup tank contained lower concentrations of both potassium and lithium, the measured concentrations only fell from 41 to about 40 ppm potassium and from approximately 3.5 to 3.0 ppb lithium.

The observed changes in the concentration and conductivity of the model boiler water were dominated by the change in level during this test. Prior to the test, 80 g lithium hydroxide was added giving an initial concentration of 45 ppm lithium. Up to the SGTR this concentration was maintained, as was the conductivity. During the SGTR, the lithium concentration fell linearly to approximately 37 ppm after which it again became constant. The fall in concentration, ~ 18%, was much greater than sampling losses, ~ 4.5%, reflecting the effects due to dilution caused by the increase in water level. During the SGTR the potassium concentration rose progressively, but it only reached a maximum concentration of about 30 ppm potassium. As this increase in concentration failed to offset the dilution effect on raising level, the overall conductivity fell during the test. Once again, as seen in Figure 5-68, the results for samples S-1 and IKP-4 were superimposable after allowing for sample line delays.

The behavior of the SORV condensate was similar to that seen in other tests. Again no lithium was detected, but generally approximately 0.5 $\mu g\ kg^{-1}$ potassium was found. Although this could be due to a change in the detection limit for potassium, the occurrence of similar effects in other tests at low pressure (for example, Test 12 (T-2001) and Test 14 (T-2065)) would suggest that some bypassing did occur. Based on the limit of detection for lithium, 0.2 ppb and on 0.5 ppb potassium and assuming that only carryover occurred, the maximum levels for carryover are $\leq$ 0.0004% (lithium) and $\leq$ 0.0016% (potassium).

Alternatively, if the potassium in SORV condensate is assumed to be due to bypassing alone, then from a comparison of the mass injection into the model boiler (40.5 ppm on average at 0.18 lbm/sec) and that lost via the SORV flow (0.5 ppb to 0.1 lbm/sec) the bypass fraction was 0.0007%.

During this test, the resistivity of the SORV condensate was very low. Based on the assumption that the volatile species was ammonia, the SORV condensate contained 30 to 50 ppm ammonia (0.012 to 0.015 MΩ cm) derived from surge tank water and about 300 ppm ammonia (0.004 MΩ cm) derived from the primary loop during the SGTR. In part, these higher concentrations were due to a hydrazine dosing error before the test, but they were also the result of the continual increase in ammonia concentrations as each test was carried out. Following this test, both the primary and secondary loops and tanks were drained and refilled with fresh water. The presence of high concentrations of ammonia and hydrazine are not expected to have affected moisture carryover.

Test 6 - 8% SORV Flow Moisture Carryover Test (T-1957)

This was conducted as a diagnostic test under conditions similar to those of the shakedown test, Test 1, but with the secondary tracer level raised to 100 ppm lithium ($\equiv pH_{25°C}$12.1) to improve the carryover detection limit. In addition, the effect of raising the steam generator water level was investigated to see if this would result in higher moisture carryover. The target initial steady-state conditions were as follows:

94

Plant Parameter	Desired Value
Primary pressure	1842 psia (127 bar)
Primary T_{hot}	580°F (304°C)
Primary flow rate	As required to maintain steam pressure
Secondary pressure	1000 psia (69 bar)
Saturation temperature	545°F (285°C)
Water level	447 in. (11.35 m) initial, ramped to 495 in. (12.57 m) final
SORV flow	8%

Before the test, the model boiler void space was drained of all water, but steam could still pass from the steam dome into the void space. The void space drain valve was kept closed during the test to prevent excessive steaming through the void space. After an initial period of operation at approximately normal water level, when the feedwater flow was maintained using both the main and auxiliary feedwater lines, the water level was raised to 495 in. over a period of 100 minutes. At this point, a plant trip occurred due to low feedwater suction pressure, itself caused by low level in the surge tank. This caused a rapid drop in water level to less than 442 in. The test was halted at this point.

Figures 5-69 to 5-75 illustrate the performance of relevant thermal-hydraulic parameters during the test. The chemistry results are summarized in Tables 5-11 and 5-12 and are shown in Figure 5-76. They are discussed in detail below.

Prior to the test, the model boiler was dosed with approximately 200g anhydrous lithium hydroxide, producing an initial concentration of 130 ppm lithium, this was reduced to 94 ppm by blowdown before the start of the test.

During the test, the concentration fell further to 82 ppm (Figure 5-76). The change, 13%, can be attributed to the dilution caused on raising the water level rather than to sampling losses which totalled about 2% of the initial inventory at the start of the test.

The lithium concentrations in the SORV condensate were above the limit of detection throughout the test. Initially, the measured level was 0.9 ppb, but this fell rapidly and a constant level of 0.5 ppb was maintained for most of the test. The condensate resistivity was relatively low throughout the test and did not follow the changes in lithium concentration. The observed value, 0.12 MΩ cm (≡ 8.2 µS/cm), would suggest the presence of about 1.4 ppm ammonia in the SORV condensate; probably this was derived from the hydrazine dosed into the surge tank and secondary loop. The change in resistivity at the start of the test cannot be explained (possibly it was due to poor mixing in the surge tank), but the change at the end of the test was due to a feed pump trip caused by low water level in the surge tank.

Based on the measured values, the carryover was in the range 0.0006% to 0.0009%. No effect due to the change in water level was detected.

Test 7 - 100% Power Moisture Carryover Test (T-1966)

This was conducted as a diagnostic test to determine if significant carryover could be detected with the model boiler operating at a high power/high water level condition. The initial steady-state conditions for the test were as follows:

Plant Parameter	Desired Value
Primary pressure	2215 psia (152.8 bar)
Primary T_{hot}	617°F (325°C)
Primary flow rate	91 lbm/sec (41.3 kg/s)
Secondary pressure	1015 psia (70 bar)
Saturation temperature	547°F (286°C)
Water level	438 in. (11.12 m) initially, gradually raised to 495 in. (12.57 m)

As configured for the Phase II tests, the SORV condenser was not scaled to handle large steam flows and could not be used alone at 100% power. However, as the 8% SORV line diverged from the main steam line at a 180° "Tee", the inlet being at 90° to both outlets, the 8% SORV line could be used to sample the main flow in a reasonably representative manner. Accordingly, this test was carried out by first running up to full power under normal operating conditions with steam passing to the feedwater heater and feedwater supplied via the main feedwater line, then with the power level maintained opening the 8% SORV line, dosing the model boiler and finally measuring the carryover.

As performed, data were collected for 30 minutes under steady-state conditions at normal water level. The water level was then raised to 495 in. over about 20 minutes. The plant was maintained at this high water level condition for about 5 minutes, during which time it was observed that the void space water level was increasing at a higher than normal rate (see Figure 5-86). This was indicative of water leakage into the void space, due probably to water froth that had flooded the dryer. Water level was then returned to normal water level by a temporary decrease in feedwater flow. Steady-state conditions were subsequently maintained for 30 minutes, followed by a further period when load was reduced to ~ 50% power.

97

Figures 5-77 to 5-83 illustrate the performance of the relevant thermal-hydraulic parameters during the test. The results obtained from the analysis of the chemical samples are summarized in Tables 5-13 and 5-14 and are shown in Figures 5-84 to 5-86. They are discussed below.

For this test the tracer level in the model boiler was set at 100 ppm lithium. In practice, the tracer was added in two stages of 80 g each, in each case it being added to the auxiliary feed line, which was then run temporarily to inject the tracer into the model boiler. On both occasions, the tracer was lost rapidly from the water in the model boiler. After the first tracer injection, the maximum concentration observed was 13 ppm lithium (compared with a calculated value of ≥ 50 ppm), this fell to about 5 ppm over 90 minutes. The second injection, see Figure 5-84, gave a greater initial increase in concentration, but again the concentration fell rapidly to 20 ppm over 80 minutes. On both occasions, the fall in concentration is believed to be due to hideout in the crevices of the model boiler. Approximately 53 minutes into the test (83 minutes after injecting the tracer), measurements of water level in the void spaces of the model boiler, Figure 5-86, indicated that the model boiler water level had been raised to the point where a two-phase mixture flooded the dryer, which resulted in leakage into the void space. At this stage there was a rapid fall in tracer concentration to approximately 10 ppm. Subsequent lowering of the water level only caused a partial recovery in the lithium concentration. A sample taken from the void space after the test indicated a concentration of 8 ppm lithium compared with 1 to 2 ppm measured after the first tracer injection, confirming that the tracer had been lost via this route.

When the S-1 and IKP-4 analytical results were compared, those for the IKP-4 line after correcting for the sample line delays were found to be only 70 to 80% of those for the S-1 sample line. This was probably due to the presence of two-phase conditions adjacent to the IKP-4 sample point at high power, so that the samples collected were mixtures of model boiler water and condensed steam. Mass balance considerations suggest that voidage may also have affected the S-1 sample point (see Section 7-2).

The concentrations detected in the SORV condensate can be separated into a period of low carryover which encompasses the first 50 minutes of the test and then the final 70 minutes dominated by the peak in the carryover. In the initial period of the test, the lithium concentration in the condensate fell from an initial value of 0.8 ppb to about 0.2 ppb in parallel with the fall in tracer concentration in the model boiler. Over this period the calculated carryover varied from 0.0016% initially to approximately 0.001% after 50 minutes. No detectable effect due to the increase in water level was observed.

After 53 minutes, carryover increased rapidly, the maximum concentration observed being 210 ppb. The increase in carryover corresponds to the point where there was an increase in the rate of accumulation of water in the model boiler void space, the latter in turn indicating that the dryer had been flooded. This can be inferred because flooding of the dryer increases the quantity of water entering the steam dome, collecting on the steam dome base plate and finally passing into the void space via the check valves. Based on the measured concentration in the model boiler, allowing for differences in delay times on sample lines, the maximum observed value corresponds to 2.3% carryover. However, if we assume a rapid initial increase in carryover on flooding the dryer, as shown in Figure 5-86, then the maximum carryover was possibly of the order of 10% to 20%.

On lowering the water level, carryover decreased. Over the first few minutes the carryover decreased approximately exponentially, but this stage was followed by a slower rate process before carryover fell to its original value. It seems probable that the relatively slow decay in carryover is due to the difficulty in cleaning surfaces or crevices contaminated with tracer in the dry steam environment beyond the dryer.

As in the previous test, the resistivity of the condensate was relatively low throughout the test and only gave minor indications of the enhanced carryover. Based on the observed value of 0.12 to 0.14 MΩ cm (7 to 8 μS/cm), the ammonia content of the condensate (and model boiler water) was approximately 1 ppm.

99

Test 8 - 10% SORV Flow, Blowdown from 442 in. to 54 in., and Operation with SGTR at Top of Tube Bundle at Four Water Levels (T-1975 - T-1979)

This test was designed to investigate the effect of a top break SGTR on carryover and/or primary coolant bypassing over a range of model boiler water levels. The test conditions were to be identical with those originally defined for Test 2.4 and were an extension of the previous test, Test 2 (T-1958), to lower water levels. As carried out, the test was split into five separate runs; an initial blowdown phase when water level was reduced from 442 in. to 54 in. and then four short SGTR injections at water levels of about 62 in., 104 in., 160 in., and 280 in. Between each SGTR phase, the level was raised and then allowed to stabilize. This sequence of operation was selected as it was believed that blowing down the model boiler after it had been dosed with lithium hydroxide would provide the most reliable way of establishing the initial tracer concentration at low level and because there were concerns over the integrity of the Inconel 600 tubing if the model boiler water was allowed to boil down to very low levels. For all five segments of the test, the target initial steady-state conditions were as follows:

Plant Parameter	Desired Value
Primary pressure	1850 psia (127.6 bar)
Primary T_{hot}	580°F* (304°C*)
Primary flow	91 lbm/sec* (41.3 kg/s)
Secondary pressure	1080 psia (74.5 bar)
Saturation temperature	554°F (290°C)

*T_{hot} and primary flow could be adjusted as required to achieve the desired secondary pressure.

In the initial phase of the test, the model boiler was dosed with lithium hydroxide while it was at normal water level. Once the concentration in the model boiler water had been defined, the level was reduced to 54 in. using the blowdown line. The blowdown rate was controlled so that the level was reduced over a period of 50 minutes, thus enabling any change in carryover behavior to be detected. As the tube bundle uncovered and the secondary side pressure dropped (due to a reduction in heat transfer surface), the auxiliary feed flow had to be decreased to maintain the rate of change in water level. Data were collected for a period of one hour commencing 10 minutes before blowdown was started.

It was originally intended to carry out the first SGTR phase at a water level of 54 in., but this proved to be impracticable due to the fall in secondary side pressure. To restore pressure, the level was raised to 62 in., but T_{hot} also had to be raised to 595°F (313°C) even with the primary loop at its maximum primary flow rate. The system was then allowed to stabilize over a period of approximately one hour before starting the SGTRs. During this first SGTR injection, the SGTR flow was halted after 13 minutes as the model boiler pressure was approaching its plant trip setpoint. During the SGTR phase, feedwater flow was adjusted as required to maintain the water level. Once the SGTR injection had been halted, level was maintained for 5 minutes and then raised to 104 in. Data were collected over the period extending from 5 minutes before the SGTR injection until the level had been stabilized at 104 in.

The remaining three SGTR phases were carried out in a manner similar to that described above, but in each case over an injection period of 25 minutes. For the SGTR injection at 104 in., T_{hot} was returned to 580°F, since sufficient water existed in the tube bundle to generate the desired secondary pressure. This value of T_{hot} was retained for the SGTR phases at 165 and 280 in., with the exception that it was mistakenly reduced slightly during testing at 165 in. after 15 minutes to keep the secondary pressure within specification. Finally, in this particular phase, the water level was raised only 3 minutes after halting the SGTR injection. For each phase of the test, the void space was drained before the test, the void space drain valve kept closed during data collection and the SGTR line warmed up before initiating the break flow. At all times feedwater was supplied via the main feedwater system.

Figures 5-87 to 5-189 illustrate the performance of the relevant thermal-hydraulic parameters during this test. They are presented subdivided into the separate phases of the test in the following pages.

Chemical samples were collected for the entire duration of the test. Unlike the thermal-hydraulic results, these cannot be treated in isolation, and in the following description they are subdivided into three major divisions, namely the blowdown phase, the SGTR injections at 62 in. and 104 in. and the SGTR injections at 165 in. and 280 in. Over the long duration of the test, the sample line flow rates tended to decrease, probably due to particulates collecting in the control valves. Neither the drop in flow nor the resetting of the flow rates are believed to have influenced the results significantly. The full results are summarized in Tables 5-15 and 5-16 and are shown in Figures 5-190 to 5-195.

Blowdown Phase (T-1975)

Prior to the blowdown phase, the model boiler was dosed with approximately 80 g lithium hydroxide to give an initial concentration of 50 ppm lithium. During blowdown, the measured concentrations fell on both the S-1 and IKP-4 sample lines. Mass balance considerations, see Section 7, indicate that this was due to the sample lines sampling steam/water mixtures, rather than due to a decrease in the concentration of the model boiler water. For the S-1 sample line, the fall in measured concentration was rapid. Nevertheless, even at a water level of approximately 130 in., the measured concentration was 12 ppm lithium, indicating that 24% of the mass sampled in the upper downcomer barrel at 425 in. was as droplets of model boiler water. When the level had fallen below 130 in., the measured concentration collapsed to values which eventually fell to only 10 to 20 ppb lithium. This change in behavior corresponded to the point when recirculation ceased within the model boiler and when superheat was developed at the top of the tube bundle. Under these conditions, the S-1 line would sample essentially pure steam. The IKP-4 sample line showed a

103

similar pattern of behavior, except that here the concentrations were generally higher than those seen on the S-1 sample line at a comparable water level, Figure 5-191, and the concentrations did not finally collapse to low values until the level had stabilized at 54 in. While steam/water mixtures in the tube bundle were expected at low levels, the drop in measured concentration from the onset of blowdown was not anticipated.

At water levels > 130 in. the observed carryover was low. Typically, the SORV condensate contained approximately 0.2 ppb lithium, which at a model boiler concentration of 50 ppm corresponds to a carryover rate of 0.0004%. Below 130 in. carryover increased, there being an initial burst of carryover as the environment above the tube bundle "dried" out and superheat was developed at the top of the bundle, followed by a sustained increased level of carryover. Estimates of the quantity released during the initial transient and of the sustained level of carryover are given in Section 7-3.

SGTRs at 62 in. and 104 in. (T-1976 and T-1977)

Before the SGTR phases of the test the primary circuit was dosed to give a concentration of 52 ppm potassium and it also contained 0.4 to 0.5 ppb lithium. Although, nominally, the makeup tank contained less potassium, in practice the concentration rose slightly during the SGTRs. Unusually the lithium concentration at first fell slightly, but then recovered to its former value by the end of the complete test.

The behavior of the two model boiler sample lines was very different during these two SGTR injections at low water level. The S-1 sample line showed little response either to the SGTR flow or to the first level change and detected only low levels of both potassium and lithium. In parallel with this behavior, the conductivity was essentially identical to that of the SORV condensate. Both effects suggest that the S-1 sample line was sampling steam during this phase of the test and that there were few droplets of model boiler water present. As the level was raised above 130 in. during the second level change, the S-1 sample recovered and again gave samples containing high concentrations of lithium and potassium.

During the SGTR injection at 62 in. and the subsequent level change, only a small response was detected using the IKP-4 sample line. In this period, both the conductivity and the potassium concentration peaked at the end of the SGTR injection, at 8 ppm potassium, before they collapsed again to 1 ppm during the level change. Concurrently, the lithium concentration increased to about 1.5 ppm during the SGTR and then fell more slowly as the system equilibrated following the level change. In contrast with the behavior at 62 in., the SGTR injection at 104 in. produced a large increase in conductivity and in potassium and lithium concentrations. In this case the potassium again peaked at the end of the SGTR injection, at 176 ppm potassium, before falling to about 70 ppm as the level was raised to 165 in. Once again, the lithium level increased throughout the SGTR injection and level change to give a final concentration of 9 ppm lithium. Finally, as the system equilibrated fully, the concentrations stabilized at about 110 ppm potassium and 10 ppm lithium.

The SORV condensate gave a complex response to both the SGTR injections and to the level changes. This consisted of a series of bursts of carryover at the start of each SGTR or level change. In each case the carryover decayed after the initial peak, but not fully before the next initiating event. For lithium the peak concentrations observed were: 62 in. SGTR, 400 ppb; 62 to 104 in. level change, 40 ppb; 104 in. SGTR, 40 ppb; 104 to 165 in. level change, 9.2 ppb, all occurring at the start of the SGTR injections or level changes. During the three later events the potassium gave a similar response, in this case the peaks at the start of the events being: 62 to 104 in. level change, 90 ppb; 104 in. SGTR, 180 ppb; 104 to 165 in. level change, 1500 ppb. In contrast with its behavior in subsequent events, the potassium concentration during the first SGTR injection at 62 in. did not show an initial peak, but built up throughout the SGTR injection to peak at 60 ppb at the end of the SGTR.

As in all other tests, the resistivity of the SORV condensate was dominated by the carryover of ammonia derived from the surge tank or from the primary loop. Typically, during the SGTR injections, the resistivity was 0.03 to 0.04 MΩ cm (≡ 25 to 33 μS/cm) and 0.11 to 0.15 MΩ cm (6.7 to 9 μS/cm) at other times. These levels correspond to 8 to 10 ppm and to 1 to 16 ppm ammonia, respectively. Similar levels were also seen in the later stages of the test. For part of the period during normal operation, the resistivity was reduced. The reason for this is unknown, but may be due to poor mixing within the surge tank as this was refilled during the test.

The analysis of carryover and/or bypassing during this part of the test is dependent on defining the concentrations in the model boiler water. These aspects are considered fully in Section 7-3. Here we may note that the IKP-4 sample line mainly sampled steam during the SGTR injection at 62 in., that at both levels there was evidence that the tracers were lost from solution and accumulated as deposits on the dry surfaces of the tube and, finally, that these deposits did not redissolve and mix fully until level was raised above about 130 in. and the recirculation reestablished. From the pattern of behavior, there was little evidence for any high level of primary coolant bypassing.

SGTRs at 165 in. and 280 in. (T-1978 and T-1979)

During the final two SGTR injections, both the S-1 and IKP-4 sample lines detected high concentrations of both lithium and potassium, indicating that both lines were sampling steam/water mixtures. Generally, the responses were similar, but as in Test 2 (T-1958), the S-1 line detected lower tracer concentrations. At 165 in. the S-1 conductivity trace showed large scale fluctuations. These are believed to be due to changes in the quantity of droplets of model boiler water reaching the primary separator, this in turn caused by small variations in water level at levels close to the critical level for the collapse of recirculation within the model boiler - for example, during the SGTR the conductivity dips coincide with small changes in water level. During the two SGTR injections, the lithium concentrations remained constant and only changed when the water level was raised, thereby causing the tracers to be diluted. For the IKP-4 sample line, the measured concentrations were about 12 ppm lithium at 165 in. and 7 ppm lithium at 280 in. As in other SGTR tests, both the potassium concentration and the conductivity rose at an approximately linear rate during the SGTR injections, but they then fell during the level change. For the IKP-4 line, the change in potassium concentration was from about 105 ppm to 200 ppm at 165 in., and from 120 ppm to 170 ppm at 280 in.

The response of the SORV condensate differed somewhat for lithium and potassium, see Figure 5-196. For lithium, the carryover decreased progressively via an exponential decay process throughout the period covering the final two SGTR injections. There was no evidence for any bursts of carryover on initiating either the SGTRs or the level change. The potassium carryover showed a similar underlying trend towards lower carryover as the test progressed, but in this case there were peaks in carryover at the start of each SGTR and during the level change. It is probable that the progressive background decrease in carryover seen for both chemical tracers is due to the slow cleanup of the steam dome and steam lines after the surfaces had been contaminated during the earlier phases of the test. An analysis of the bursts of potassium carryover is given in Section 7-3.

Test 9- 10% SORV Flow, Blowdown from 442 in. to 54 in. and Operation with SGTR at Bottom of Tube Bundle at Four Water Levels (T-1988 - T-1992)

This test was a repeat of Test 8, but was designed to investigate the difference in carryover and/or primary coolant bypassing caused by a change in break location from the top to the bottom of the tube bundle. As before, the test was split into five separate sections: an initial blowdown phase when water level was reduced from 442 in. to 54 in. and then four short SGTR injections at water levels of about 64 in., 102 in., 165 in. and 285 in. For each part of the test the target steady-state initial conditions were as follows:

Plant Parameter	Desired Value
Primary pressure	1850 psia (127.6 bar)
Primary T_{hot}	580°F* (304°C*)
Primary flow	91 lbm/sec* (41.3 kg/s)
Secondary pressure	1080 psia (74.5 bar)
Saturation temperature	554°F (290°C)

106

*T_{hot} and primary flow could be adjusted as required to achieve the desired secondary pressure.

In the initial phase of the test the model boiler was dosed with lithium hydroxide while at normal water level. Once the tracer concentration in the model boiler had been defined, the level was reduced to 54 in. As in the previous test, the blowdown rate was controlled such that the level reduction took about 50 minutes. Data were collected over a period extending from about 10 minutes before blowdown commenced until the level had stabilized at 54 in. As the tube bundle uncovered and the secondary pressure dropped, the feed flow was reduced to maintain the rate of change in water level.

After blowdown was complete, the system was allowed to equilibrate for about 80 minutes before the first SGTR injection was initiated. During this period water level was raised to 64 in. and T_{hot} increased to 595°F (313°C) at maximum primary flow in order to restore secondary pressure to the target level. During the first SGTR cycle at 64 in. data were collected for 5 minutes before initiating the SGTR, then during the 25 minutes of SGTR injection, a further 5 minutes of steady-state operation and finally during the level change to 102 in. During this period, the feedwater flow was adjusted first to maintain water level and then to increase it to 102 in. For the remaining SGTR cycles an identical sequence was followed, the only exception being that T_{hot} could be reduced to 580°F in all tests as sufficient water existed in the tube bundle at 102 in. and above to generate the required secondary pressure. As in other tests, the model boiler void space was drained before the tests, the void space drain valve was kept closed during the individual test phases and the SGTR line warmed up before each SGTR injection. At all times feedwater was supplied via the main feedwater system.

Figures 5-197 to 5-299 illustrate the performance of the relevant thermal-hydraulic parameters during the test. They are presented subdivided into the separate phases of the test in the following pages.

Chemical samples were collected for the entire duration of the test. As in Test 8, the results are subdivided into three major divisions, namely the blowdown phase, the SGTR injections at 64 in. and 102 in. and the SGTR

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injections at 165 in. and 285 in. For this test an additional sample line was installed in the model boiler blowdown line in an attempt to collect representative samples at low water level from a point where only single phase conditions should exist. In practice, the blowdown samples were nonrepresentative and this sample line was not used in other tests. Because of the long duration of the test, the sample line flow rates fell throughout the test and had to be reset on several occasions. Neither the drop in flow rate, nor the resetting of the flow rates are believed to have influenced the results significantly. The full results are summarized in Tables 5-17 and 5-18 and are shown in Figures 5-300 to 5-306.

Blowdown Phase (T-1988)

Before the blowdown phase the model boiler was dosed with approximately 100 g lithium hydroxide. After equilibration both the IKP-4 and blowdown lines indicated an initial concentration of 65 ppm lithium, while the S-1 line indicated only 58 ppm. The reason for this discrepancy, which was also detected by conductivity, is unknown and similar differences were only seen in one other test. It is considered that the IKP-4 and blowdown lines give the more representative results for this test. During blowdown the measured concentrations fell on all three sample lines. For both the S-1 and blowdown lines the fall in concentration was rapid. Based on the conductivity the measured S-1 concentrations collapsed to very low values, about 50 to 100 ppb lithium, once the level had fallen below 120 in. While this behavior was expected for the S-1 sample line, a similar behavior was not expected for the blowdown line. Two explanations can be suggested for the observed behavior. One is that steam/water mixtures develop in the area of blowdown line take-off point, alternatively, the take-off point may be in a region where it samples an unmixed stream of water from the downcomers as this passes over the tubesheet. In practice, both effects contributed to the observed behavior (see Section 7-3). As in the previous test, Test 8, the IKP-4 sample line showed a similar pattern of behavior, but again the concentrations fell more slowly than did those on the other sample lines and here the concentrations only fell to very low levels once the level had stabilized at 54 in.

108

At water levels > 150 in. carryover was low, typically ≤ 0.3 ppb lithium. At a model boiler concentration of 65 ppm this corresponds to < 0.0003 to 0.0005%. Below 130 in. carryover increased, there being an initial burst of carryover, as the environment above the tube bundle "dried" out and as superheat was developed at the top of the bundle, followed by a sustained increased level of carryover. Estimates of the quantity released during the initial transient and of the sustained level of carryover are given in Section 7-3.

SGTRs at 64 in. and 102 in. (T-1989 and T-1990)

Before the SGTR phases of the test the primary circuit was dosed to give a concentration of 45 ppm potassium. As the makeup tank contained less potassium, 39 to 42 ppm, the concentration in the primary loop fell slightly as the test progressed. At the start of the test the lithium concentration was 4.8 ppb; once again the concentration fell as the test proceeded, since the makeup tank contained no lithium.

The three model boiler sample lines gave different responses during these two SGTR injections. As in Test 8, the S-1 sample line showed little response to either the SGTR flows or to the level change and the conductivities were again identical to those of the SORV condensable. Both effects suggest that the S-1 sample line was sampling essentially pure steam during this phase of the test. Compared with the top break test, Test 8, the potassium concentrations detected in this test were greater - the reverse of what might be expected if a top break promoted primary coolant bypassing. As the water level was raised to 165 in., the S-1 sample recovered and once again gave samples containing high concentrations of both lithium and potassium.

In contrast with the behavior seen in the top break test, Test 8, the IKP-4 sample line responded strongly to the SGTR flow during both SGTR injections. During the SGTR injection at 64 in. the potassium concentration increased to 390 ppm (cf 8 ppm in Test 8), while at 102 in. it increased to 280 ppm (cf 176 ppm in Test 8). During the level change to 102 in. and subsequent equilibration the potassium concentration fell to about 20 ppm, while after the second level change the concentration stabilized at about 130 ppm

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potassium. Throughout the SGTR injections the lithium concentrations remained relatively low, < 5 ppm, and only increased to a stable higher level of about 26 ppm lithium when the level was increased to 150 in. The concurrent measurement of low lithium and high potassium concentrations, when combined with data from the other low level tests, indicates that hideout occurred at these low levels. An analysis of this behavior is given in Section 7-3.

Throughout this period of the test the blowdown line gave a response which was intermediate between that of the S-1 and IKP-4 sample lines. Thus, the response resembled that of the IKP-4 sample line, but with the concentrations very much reduced (by factors of up to 70). Again, this would indicate either very little mixing between the auxiliary feedwater and the model boiler water at the position of the blowdown line take-off, or local high voidage at the take-off point.

As in Test 8, the SORV condensate gave a complex response to both the SGTR injections and to the level changes. These consisted of large bursts of carryover at the start of the two level changes and of slightly smaller bursts of carryover during the SGTR injections at 64 in. and 102 in. (the latter in contrast with Test 8). As in the previous test, these bursts of carryover had not decayed fully before the next initiating event. For the level changes the peak concentrations were: 64 to 102 in., 60 ppb lithium and 980 ppb potassium; 102 to 165 in., 20 ppb lithium and 350 ppb potassium. During the SGTRs there were no transient peaks in lithium concentration during either SGTR injection and only two peaks in potassium concentration during the SGTR injection at 102 in., of 340 and 750 ppb. Estimates of carryover and for bypassing based on these values are given in Section 7-3.

As in the other tests, the resistivity of the SORV condensate was dominated by carryover of ammonia derived from the primary loop water or from the surge tank water. Typically, the levels were about 0.03 MΩ cm (≡ 33 μS/cm) during the SGTR injections and about 0.09 MΩ cm (≡ 11 μS/cm) at other times. These correspond to about 10 ppm and 2.2 ppm ammonia, respectively. Similar values were also observed in the later stages of the test.

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110

SGTRs at 165 in. and 285 in. (T-1991 and T-1992)

In the final two SGTR injections all three model boiler sample lines generally responded in a similar manner to that seen in Test 8. At both water levels the S-1 sample line again detected lower concentrations then the IKP-4 line, with the difference more pronounced at the lower water level. Once again, at 165 in. the conductivity trace for the S-1 sample line showed large variations, which were probably due to changes in conditions above the tube bundle caused by small variations in water level. The blowdown line gave a response which changed as the water level was raised. Thus, at 165 in. the response was identical to that of the S-1 sample line, while at 285 in. it was identical to the IKP-4 line. The reason for this change is not known.

During both SGTR injections the lithium concentrations remained constant and only changed when the water level was raised. For the IKP-4 sample line the measured concentrations were about 26 ppm lithium at 165 in. and 15 ppm lithium at 285 in. In both SGTR injections the potassium concentration and the conductivity rose at an approximately linear rate, but then fell during the level change. For the IKP-4 sample line the changes in potassium concentration were from about 130 ppm to 192 ppm at 165 in. and from 125 ppm to 166 ppm at 285 in.

In this phase of the test the SORV condensate gave a simple response which was identical for both tracers. In each case the measured carryover decreased progressively via an exponential decay process, see Figure 5-306, throughout the period covering the final two SGTR injections. There was no evidence for any increase in carryover caused either by the SGTR flows or by the final level change. Again, it is probable that the observed behavior was due to the slow removal of lithium and potassium from the surfaces of the steam dome and steam lines after these had been contaminated during the earlier phases of the test.

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Test 10 - Overfill Transient with SGTR at Top of Bundle, 10% SORV Flow (T-1998)

This test was designed to simulate an overfill transient caused by an SGTR at the top of the tube bundle in an isolated steam generator. In this transient the SGTR flow will cause both the secondary level and pressure to rise, but periodically the pressure will be relieved by the opening of the safety relief valve. In this first test the target initial steady-state test conditions were similar to those for Tests 1, 8 and 9. They were as follows:

Plant Parameter	Desired Value
Primary pressure	1850 psia (127.6 bar)
Primary T_{hot}	580°F (304°C)
Primary flow rate	14 lbm/sec (6.4 kg/s)
Secondary pressure	1000 psia (69 bar)
Saturation temperature	545°F (285°C)
S/G Water level	442.5 in. (11.24 m)
SORV flow	2%

Throughout the test feedwater was supplied via the normal auxiliary feedwater line. Before the test the model boiler void space was drained of water periodically, but steam could still pass from the steam dome into the void space. During data collection the void space drain valve was kept closed to prevent excessive steaming through the void. Before the SGTR injection the SGTR line was warmed up for at least 5 minutes, it was then lined up with the top break element and the SGTR flow initiated.

For the first 30 minutes of the test steady-state conditions were maintained with an SORV flow rate of 2%. After 30 minutes the SGTR flow was initiated and the auxiliary feed flow halted, but the 2% SORV flow was continued as it was hoped to maintain SORV condensate sampling. Since neither the level nor the secondary pressure rose, the auxiliary feed flow was restarted after 5.7 minutes and the 2% SORV flow halted after 14 minutes; thereafter both level and pressure rose.

When the model boiler pressure reached 1200 psig, a 10% SORV flow was initiated by opening both SORV lines. A 10% rather than an 8% SORV flow was used as this was more representative of the actual flow through a safety relief valve. The SORV flow was allowed to continue until the model boiler had depressurized to 1000 psig. This cycle of pressure and level increase followed by a 10% SORV depressurization was carried out a total of eight times. Before the final depressurization the water level had increased to about 530 in. In the final cycle the 10% SORV flow was not halted at 1000 psig, instead the model boiler was allowed to boil down to < 50 in. to detect any change in carryover on reducing water level. At this water level both the SGTR and SORV flows were halted, while the auxiliary feed flow was restarted to stabilize the level at 50 in. This condition was maintained for 30 minutes to permit chemical sampling from the model boiler.

During this test, after approximately 2 hours, it was found that the shock wave propagating through the SORV condensate pipework on initiating the 10% SORV flow had caused the SORV condensate drain tube to jump out of the drain pipe leading to the SORV condensate collection tank. As a result, measurements of the total SORV mass flows derived from the SORV collection tank level are not available for the complete test. In addition, due to the slow draining of the SORV condenser, plus the delays down the SORV condensate sampling line, it was not possible to collect satisfactory samples during the depressurization cycles. For these reasons the test was repeated, see Test 11 (T-2003).

Figures 5-307 to 5-317 illustrate the performance of the relevant thermal-hydraulic parameters during the test. The results obtained from the analysis of the chemical samples are summarized in Tables 5-19 and 5-20 and are shown in Figures 5-318 to 5-319. They are described below.

For this test the primary loop was dosed to 16 ppm potassium, while the makeup tank contained < 10 ppm; consequently the concentration fell as the test proceeded. The lithium concentration was low, about 0.5 ppb, and fell to < 0.2 ppb during the test.

At the start of the test the model boiler was dosed with 18 g lithium hydroxide giving a concentration of 10 ppm lithium. In the early stages of the test, up to 75 minutes, the concentration fell slowly to 8.5 ppm, while the potassium concentration rose at a constant rate to 12 ppm potassium. These changes are consistent with the level change and sampling losses. Beyond 75 minutes the lithium concentration fell more rapidly, reaching 2 ppm by the end of the test. At the same time the conductivity fell and so eventually did the potassium concentration. Mainly, these changes were due to the loss of water to the void space of the model boiler when the level rose above the dryer, but some losses could also be due to hideout. In total, the mass is estimated to have risen from about 1050 lbm at the start of the test to about 5300 lbm by the end of the overfill phase. Of this, very little was lost by venting and up to 3000 lbm would be displaced into the void space. Analysis of the void space confirmed the presence of water displaced from the model boiler.

Prior to the final boildown phase of the test, both the S-1 and IKP-4 sample lines gave identical results, as seen in the other tests at normal water level. During the boildown the IKP-4 concentrations increased as expected, but those measured on the S-1 sample line fell to very low values. The latter behavior was also seen in the other low level tests, e.g., Tests 8 and 9, and was indicative of a steam environment at the S-1 sample point.

In theory, the SORV condensate sample line should only have operated for the first 44 minutes of the test, during each pressure relief cycle and then during the final boildown. In practice, however, there was sufficient leakage past the SORV valves or slow draining of the SORV condenser to ensure that the line flowed continuously, except immediately after venting. In general, and except during venting, the observed carryover was low, approximately 0.2 ppb, while the resistivity matched that seen in other tests. The latter indicated about 0.5 ppm ammonia (0.25 MΩ cm) in the condensate before the SGTR, 25 to

35 ppm (0.015 to 0.02 MΩ cm) during the SGTR and about 0.08 ppm ammonia (1 MΩ cm) after the final boil down. During a number of the pressure relief cycles higher carryover was observed. The results observed were variable, but in one cycle the SORV condensate concentrations rose to 30 ppb lithium and 170 ppb potassium. During the boildown phase no increase in carryover was seen, but sampling was not maintained beyond the point where higher carryover was seen in other tests, i.e., at water levels < 100 inches.

Based on the limit of detection of 0.2 ppb, the carryover generally was < 0.002% (lithium) and < 0.0004% (potassium). The maximum observed levels during venting corresponded to 0.09% (lithium) and 1.13% (potassium).

Test 11 - Overfill Transient with SGTR at Top of Bundle, 10% SORV Flow (T-2003)

This test was a repeat of Test 10, but with the SORV condensate sample point relocated to collect almost instantaneous SORV condensate samples during the pressure relief cycles. During the first 30 minutes of steady-state operation, the plant conditions were as follows:

Plant Parameter	Desired Value
Primary pressure	1850 (127.6 bar)
Primary T_{hot}	580°F (304°C)
Primary flow rate	12.5 lbm/sec (5.7 kg/s)
Secondary pressure	1000 psia (69 bar)
Saturation temperature	545°F (285°C)
Water level	442.5 in. (11.24 m)
Initial SORV flow	2%

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Throughout the test, feedwater was supplied via the normal auxiliary feedwater line. Before the test, the model boiler void space was drained of water periodically, but steam could still pass from the steam dome into the void space. During data collection, the void space drain valve was kept closed to prevent excessive steaming through the void space. Before the SGTR injection, the SGTR line was warmed up for at least 5 minutes, it was then lined up with the top break element and the SGTR flow initiated.

For the first 30 minutes of the test, steady-state conditions were maintained with a 2% SORV flow rate. After 30 minutes, the transient was started by initiating the SGTR flow and by simultaneously halting the 2% SORV flow and the auxiliary feedwater flow. After 43 minutes the secondary pressure had increased to 1200 psig. At this point, the first pressure relief cycle was initiated by opening both the 2% and the 8% SORV flow lines. Over 1.33 minutes the pressure fell to 1000 psig, the SORV flow was then halted. Further pressure relief cycles, each of 1.25 minutes were carried out after 59, 77, 98 and 130 minutes. After 45.5 minutes the auxiliary feed flow was restarted as water level was not rising. The flow rate was further increased after 78.25, 99.25 and 131.25 minutes. After 160 minutes, when the water level had reached 530 in., the auxiliary feedwater flow was stopped and a final pressure relief cycle started. On this occasion, the 10% SORV flow was not halted at 1000 psig, instead the water level was allowed to boil down to about 50 in. After 190 minutes, when the level had reached 50 in., the 8% SORV line was closed reducing the total SORV flow to 2%. This state was maintained until 195.5 minutes, when the SORV flow rate was again increased to 10% for a short period (72 seconds) to see if an increase in the SORV flow rate affected moisture carryover. After 197.5 minutes, the SGTR flow was stopped and the auxiliary feed flow was again restarted to maintain water level at 50 in. This final steady-state condition, with a 2% SORV flow rate, was maintained for a further 30 minutes to permit additional chemical monitoring of the model boiler water.

Figures 5-320 to 5-336 illustrate the performance of the relevant thermal-hydraulic parameters during the test. Chemical samples were collected throughout the test. While the standard method of sample collection was followed for the primary, S-1 and IKP-4 sample lines, a modified procedure was

116

adopted for collecting the SORV condensate samples. For this, the sample line was disconnected at its take-off point and grab samples were collected during the pressure relief cycles directly from the sample point at the base of the loop seal "U" tube mounted below the SORV condenser. Because the sample did not flow continuously to the sample hut, continuous resistivity results are not available for this test. The analyzed results are summarized in Tables 5-21 and 5-22 and are shown in Figures 5-337 to 5-341. These results are described below.

The behavior of both the primary loop and the model boiler were similar to that observed in the first trial, Test 10. There were, however, some differences. Thus, on this occasion, the primary loop concentration rose from 8 to 9 ppm potassium since the makeup tank concentration of 10 ppm was greater than that of the primary loop. In addition, the model boiler water concentration began to decrease even before the first SORV cycle. The latter probably reflects the more rapid increase in level with the 2% SORV line isolated. Again, as in the previous test, boildown caused the S-1 and IKP-4 sample lines to respond differently, but at higher water levels the sample lines gave identical results.

Grab SORV condensate samples were collected during steady-state operation, during each pressure relief cycle and during the final boildown phase of the test. During the initial period of steady-state operation carryover was low, < 0.2 ppb. Low carryover was also seen during boildown until about 190 minutes, when low level, < 100 inches, was reached. Carryover then increased to 20 to 30 ppb potassium and to 1 to 1.5 ppb lithium, as seen in other tests at low level, see Section 7-3. During the period at low level there was a larger spike in carryover, at 196 minutes. This was caused by increasing the steam flow from 2% to 10% SORV for a short period (195.5 to 196.7 minutes).

During each pressure relief cycle a spike in carryover was observed. In each cycle the 2% and 8% SORV lines were both opened for 75 seconds. This caused a flow of SORV condensate for about 150 seconds. During the first four cycles, samples were collected at 30 second intervals, but for the final two cycles they were collected every 15 seconds. The results are shown in Figures 5-399 to 5-341. For each cycle the results show that there was a burst of carryover at the start of the pressure relief cycle. This resulted in high concentration in the first few SORV condensate samples collected, but over 60 seconds the concentrations returned to relatively low levels. As the test proceeded and the model boiler water level rose, the relative concentrations detected in each cycle increased; this was particularly apparent in the final two cycles. The observed behavior suggests that there was a transient release of water from the model boiler as steam production rates increased in response to the opening of the SORV steam lines. The analysis of the behavior is given in Section 7-3.

Test 12 - Transient Test with SGTR at Top of Tube Bundle, 2% - 10% SORV Flow (T-2001)

This test was designed to simulate the plant conditions which would exist following an SGTR at the top of the tube bundle in one steam generator of a 4-loop PWR, occurring in conjunction with a stuck-open safety relief valve and at a time when there was no off-site power available. The initial target steady-state conditions at 60% power for the test were as follows:

Plant Parameter	Desired Value
Primary pressure	2295 psia (158.3 bar)
Primary T_{hot}	595°F (313°C)
Primary flow rate	91 lbm/sec (41.3 kg/s)
Secondary pressure	1050 psia (72.4 bar)
Saturation temperature	551°F (288°C)
Water level	442.5 in. (11.24 m)

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Steam flow	As required to maintain desired steam pressure
Feedwater temperature	390°F (199°C)

The calculated and actual conditions for the SGTR phase of the test are shown in Figure 5-353. As calculated, the early stages of the transient predict that the reactor scrams after about 600 seconds due to low pressurizer pressure, closely followed by a turbine trip and by the cessation of the main feedwater flow. Auxiliary feedwater flow commences within 60 seconds. As steam cannot be dumped to the condenser after the reactor scram when there is no off-site power, it is vented to atmosphere via the safety relief valves. After about 1850 seconds low steam pressure closes all the main steam isolation valves, isolating the affected steam generator. No operator intervention is assumed until 30 minutes after the reactor scram, when steps are taken to control the leak rate by reducing the safety injection flow rate and hence the primary circuit pressure. In the transient followed it is assumed that the operators will not halt the auxiliary feedwater supply to the faulted steam generator, but that they will control the flow to maintain normal water level for as long as is practicable. Until the affected steam generator is isolated, all four steam generators will contribute equally to the total steam flow escaping via the stuck open safety relief valve. However, once the steam generator is isolated, all the escaping steam is derived from the affected steam generator. Thus, the steaming rate for the affected steam generator rises from 2% to 8%, the maximum steam flow rate for the relief valve, when the steam generator is isolated.

In practice, steady-state conditions at about 60% power were maintained for 30 minutes before the start of the transient. During this time feedwater was supplied via both the main and the auxiliary feedwater lines. The use of the auxiliary feed line at this stage was an error, but its effect is considered minimal. In addition, the main feedwater temperature was lower, 369°F, than the target value, because the feedwater heater had about 25% of its tubes plugged. Steam was removed using both the main steam line and the 2% SORV line, the latter to establish SORV condensate sampling before the SGTR was initiated. Before the test the model boiler void space was drained of water, but steam could still pass from the steam dome into the void space. The void space drain valve was kept closed during the transient to prevent excessive steaming through the void space. Before the SGTR injection, the SGTR line was warmed up for at least 5 minutes and it was then lined up with the top break element and the SGTR flow initiated.

After 30 minutes, the transient was started by initiating the SGTR flow and the primary loop pressure transient. After 38.5 minutes it was discovered that the auxiliary feed line was in use, and it was secured. Water level control continued to be maintained using the main feedwater line. After 40 minutes the reactor scram and turbine trip were simulated by initiating the T_{hot} transient and by closing the main steam and main feedwater lines. The 2% SORV line remained open to simulate the stuck-open safety relief valve. At the same time the auxiliary feedwater line was reopened, but as water level rose with only a 2% SORV flow, the auxiliary feed flow was again halted. Steam pressure in the model boiler rose sharply when the main steam and main feedwater lines were closed, and after 42.5 minutes the 8% SORV line was opened to prevent the model boiler safety relief valve opening. A plant trip occurred at the same time as the 8% SORV line was opened, but this did not seriously affect either the T_{hot} or the primary pressure transients. However, the model boiler water level experienced a sudden drop due to the collapse of the voidage in the bundle region. The plant was returned to test conditions immediately and the transient continued. After 52 minutes, the main steam line was further isolated using the hand-operated isolation gate valve, HCV-2203, to prevent condensation in the steam line dead leg.

Steaming was allowed to continue using only the 2% SORV line until 60.8 minutes had elapsed (30.8 minutes, 1850 seconds, into the transient). At this point, steam generator isolation was simulated by opening the 8% SORV line in addition to the 2% SORV line. As in other tests in the modified program, a 10% SORV flow was used rather than an 8% SORV flow, as this gave a better simulation of the flows through a safety relief valve. After 70 minutes the second stage of the primary pressure transient was commenced, in this case to simulate the actions of the operators to control the SGTR flow rate. After 83.75 minutes the auxiliary feed flow was restarted to maintain water level. The flow was then maintained until the water level again started to rise as the SORV flow rate fell. During the final stages of the test, water level rose even without any auxiliary feed flow, as it did in Test 2.1. The transient was allowed to continue until 363.33 minutes had elapsed, 20,000 seconds after initiating the transient, when both the SGTR and the SORV flows were halted. Data were then collected for a further 30 minutes to permit additional monitoring of the model boiler sample lines.

Figures 5-342 to 5-353 illustrate the performance of the relevant thermal-hydraulic parameters during the test. Chemical samples were collected for the entire duration of the test. During the test, both the model boiler and the primary loop sample line flow rates fell progressively and had to be reset on a number of occasions. For the model boiler lines, the loss of flow rate was particularly rapid; this was probably due to particulates disturbed by the initial operation at 60% power. There was no evidence to indicate that the changing sample line flow rates had any effect on the results. The analytical results are summarized in Tables 5-23 and 5-24 and are shown in Figures 5-354 and 5-355. These results are described below.

Before the test the primary loop concentration was 8 ppm potassium. This level was matched in the makeup tank before the test began and it was also matched when the makeup tank was refilled and redosed during the test over the period from 105 to 153 minutes. Because the levels were the same, the potassium concentration did not alter during the test. Throughout the test the lithium concentrations were low. Initially the level was 0.5 ppb lithium, but this fell to about 0.2 ppb as the test proceeded. Even though the potassium concentration remained constant the conductivity fell during the test. Probably this was due to the changing concentrations of ammonia and hydrazine in the primary loop as fresh makeup water was added, these changes being more apparent due to the lower potassium concentrations and consequent lower pH.

The behavior of the model boiler water was more complex than in other tests, due to the effects of the initial change in water level and to the varying SGTR leak rate and increasing water level towards the end of the test. At the start of the test, the model boiler was dosed with about 18 g lithium hydroxide to give a concentration of 11 ppm lithium. This level was maintained for the first 12.5 minutes of the SGTR, until the coincident opening of the 8% SORV line and the plant trip caused a rapid loss in water level. In other tests, for example Test 2 (T-1958), boiling down to reduce level caused an increase in concentration, but here it resulted in a fall to about 7 ppm. It is possible that the reduction in concentration was due to hideout as the voidage collapsed, but it is also possible that there was an accidental loss of water during the plant trip. Accompanying the fall in concentration were changes in conductivity in the S-1 and IKP-4 samples. These changes were, however, different; the S-1 conductivity decreasing, the IKP-4 conductivity increasing, Figure 5-355. Similar effects were seen in other tests during boildown and blowdown, see for example Figures 5-44, 5-57, 5-319, 5-338 and 5-390.

After the initial level change, the changes in lithium concentration followed those seen in other tests, there being an overall decrease in concentration by 30%. This was due mainly to the late stage increase in water level rather than to the sampling losses of about 6%. In contrast with the constant rate of increase in potassium concentrations seen in steady-state SGTR tests, in this test the rate of increase in potassium decreased as the test proceeded and eventually the concentration fell. This is consistent with the falling leak rate as the test proceeded and with the increase in level at the end of the test when leak rates were low. In the final stage of the transient, the fall in the potassium concentration was due, even after allowing for the 10% SORV flow, to the increase in water level caused by adding primary loop water of lower concentration than that present in the model boiler. As seen in other tests at normal or high water level, essentially identical results were obtained on both the S-1 and IKP-4 sample lines.

The SORV condensate behaved in a similar way to that seen in other SGTR tests. Thus, in general, carryover was very low, 0.2 ppb or less, while the resistivity showed the step changes believed to be due to the differences in ammonia levels in the primary and secondary loops. The latter indicate SORV condensate ammonia concentrations of 1.7 and 3.7 ppm (0.5 and 0.07 MΩ cm) before and after the SGTR and 10 ppm (0.03 MΩ cm) during the SGTR.

On five occasions, Figure 5-54 and Table 5-23, individual samples showed higher carryover. While these may be due to contamination, two of these samples were collected when rapid changes in level or pressure were occurring; in other tests similar rapid changes also gave bursts of higher carryover. Based on the general level of carryover and a limit of detection of 0.2 ppb, the normal level of carryover was $\leq$ 0.003% (lithium) and $\leq$ 0.0006% (potassium); estimates of the transient releases are given in Section 7-3.

Test 13 - 100% Power Moisture Carryover Test with Dryer Bypassed (T-2069)

This was carried out as a diagnostic test to determine if carryover would be significantly increased when the model boiler was operating at high power with the dryer bypassed. The test was carried out in a similar manner to Test 7 (T-1966) (with dryer in operation), but the increase in level was limited to about 465 in., at which point the primary separator was fully flooded but not the entrance plenum to the dryer assembly (the bypass pathway). The initial steady-state conditions were as follows:

Plant Parameter	Desired Value
Primary pressure	2250 psia (155.2 bar)
Primary test	615°F (324°C)
Primary flow rate	91 lbm/sec (41.3 kg/s)
Secondary pressure	1015 psia (70 bar)
Saturation temperature	547°F (286°C)
Water level	442 in. (11.24 m)
Steam flow rate	As required to maintain desired steam pressure

As in Test 7 (T-1966), the test was carried out by first running up to full power under normal operating conditions with steam passing to the feedwater heater and feedwater supplied via the main feedwater line. Then, with the power level maintained, the 8% SORV line was opened, the model boiler dosed and, finally, the carryover measured.

As performed, data were collected for 20 minutes under steady-state conditions at normal water level. The water level was then raised to about 465 in. over about 15 minutes. The plant was maintained at this level for a further 15 minutes, and finally returned back to normal water level. As in other tests, the model boiler void space was drained of water prior to the test, and during the test the void space drain valve was kept closed to prevent excessive steaming through the void space. Throughout the test there was a small leak of approximately 84.5 lbm/hr (10 gallon/hr) at the feedwater connection to the upper shell of the model boiler.

Figures 5-356 to 5-369 illustrate the performance of the relevant thermal-hydraulic parameters during the test. The results obtained from the analysis of the chemical samples are summarized in Tables 5-25 and 5-26 and are shown in Figure 5-370. They are discussed below.

For this test, 50 g lithium hydroxide were added to the model boiler to give an initial concentration estimated to be 35 ppm lithium. As the test progressed, hideout again was observed, the concentration falling to approximately 14 ppm over 80 minutes. Since the dryer entrance plenum was not flooded, no tracer was lost to the void spaces and no rapid fall in tracer concentration was observed.

Over the initial phase of the test, corresponding to the period at normal water level, low carryover was observed. The measured levels, 0.6 ppb falling to 0.4 ppb lithium, correspond to a carryover rate of 0.0023% to 0.0017%, comparable to that with the dryer present. On raising water level, the carryover increased reaching a maximum of 2.2 ppb lithium at 465 inches. At this point the carryover was 0.012%. On reducing water level, carryover again decreased.

124

As in other tests, the SORV condensate resistivity was dominated by carryover of volatile species in the secondary loop. Again assuming that the volatile species is ammonia, the resistivity, 0.3 to 0.4 MΩ cm (2.5 to 3.3 µS/cm) corresponds to 0.25 to 0.35 ppm ammonia.

Test 14 - 10% SORV Flow with SGTR at Bottom of Tube Bundle and with Dryer Bypassed (T-2067)

This was designed as a two-part steady-state test at intermediate secondary pressures, with the secondary separators bypassed and with the SGTR injection at the bottom of the tube bundle. The first half of this test was carried out at normal water level and was a repeat of Test 4 (T-1982). It was aimed at eliminating the variability associated with the efficiency of different dryer designs and at defining the effectiveness of the primary separator alone. The second half of the test was carried out at low water level, 102.5 in. Here the test was designed to show if enhanced carryover occurred at the reduced pressures and temperatures which would exist at an intermediate stage in an overall SGTR/SORV transient. The target initial steady-state conditions were as follows:

Plant Parameter	Desired Value
Primary pressure	557 psia (38.4 bar)
Primary test	470°F (243°C)
Primary flow rate	As required to maintain desired secondary pressure
Secondary pressure	305 psia (21 bar)
Saturation temperature	419°F (215°C)
Water level	442.5 in. (11.24 m)
SORV flow	10%

Throughout the test, feedwater was supplied via the auxiliary feedwater line. In this line there was a small leak of about 84.5 lbm/hr (10 gallon/hr) at the upper shell feedline connection. Prior to the test the model boiler void space was drained periodically of condensate, but steam could still pass from the steam dome into the void space. During data collection the void space drain valve was kept closed to prevent excessive steaming through the void space. As in other tests, the SGTR was warmed up for at least 5 minutes before being lined up with the bottom break element and the SGTR flow initiated.

In the first half of the test, 15 minutes of steady-state data were collected before initiating the SGTR flow. After 60 minutes, the SGTR flow was halted and 7 minutes later the level was reduced by blowdown to 102.5 in., the latter taking approximately 20 minutes. Conditions were allowed to stabilize for a further 20 minutes after which the SGTR flow was reinitiated and allowed to continue for a further 60 minutes. The test was completed by a final 30 minute period of steady-state operation at 102.5 in.

Figures 5-371 to 5-388 illustrate the performance of the relevant thermal-hydraulic parameters during the test. Samples were collected for chemical analysis throughout the test. The results are summarized in Tables 5-27 and 5-28 and are shown in Figures 5-389 and 5-392. The results are described below subdivided into the periods of operation at different water levels.

Normal Water Level

Before the test, the primary loop was dosed to give a concentration of 50 ppm potassium. As the test proceeded, the potassium level rose slightly since the makeup tank contained a higher concentration. As in other tests, the lithium concentration fell during the test because the makeup tank was free of lithium contamination.

Before the test, the model boiler was dosed with about 65 g lithium hydroxide to give a concentration of 36 ppm lithium. Both before and during the test the lithium concentration remained essentially constant. In general, this is consistent with the absence of any dilution due to a level change and to the

126

small sample line losses during the first half of the test, 1.1%. During the SGTR injection the potassium concentration increased at an almost constant rate to a maximum concentration of 61 ppm, with the maximum occurring a few minutes after the SGTR flow had ceased. As in all other SGTR tests at normal water level, the observed concentrations, and in general the conductivities for the S-1 and IKP-4 sample lines, can be superimposed when allowance is made for the different sample line delays.

The behavior of the SORV condensate differed slightly from that seen in the corresponding test with the dryer in operation. In this test carryover was not detectable when there was no SGTR flow, but it was detectable during the SGTR injection with, in addition, there being a peak in carryover when the flow was initiated. While similar effects were seen in the earlier test, Test 4 (T-1982), they were not well resolved and appeared to be mainly restricted to the potassium carryover. The present results may be interpreted either in terms of carryover alone or as primary coolant bypassing with an increased level of secondary carryover.

If we assume carryover alone, then carryover during steady-state SGTR injection can be estimated from the typical SORV condensate levels of 0.2 ppb lithium and 0.3 to 0.4 ppb potassium and from the maximum model boiler water concentrations of 36 ppm lithium and 61 ppm potassium. These give estimates of 0.0006% (lithium) and 0.0005 to 0.0007% (potassium). If we assume bypassing, then based on a comparison between the mass of potassium entering the model boiler to that leaving in the SORV flow, the steady-state bypass fraction was 0.0009 to 0.0012%. Estimates for the transient release at the start of the SGTR injection are given in Section 7-3.

As in other tests, the resistivity of the SORV condensate showed a marked change during the SGTR. Typically, the observed values were 1.4 to 1.8 MΩ cm (0.55 to 0.70 μS/cm) during normal operation and 0.02 to 0.024 MΩ cm (42 to 50 μS/cm) during the SGTR injection. Assuming that this is due to ammonia, these correspond to 0.04 to 0.06 ppm ammonia during normal operation and 18 to 25 ppm ammonia during the SGTR injection. Similar values were seen in the second stage of the test.

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Blowdown to 102.5 in. Water Level

During blowdown the S-1 and IKP-4 sample lines gave very different responses. As expected, the concentrations as measured by the S-1 sample line collapsed as the level was reduced and as progressively drier conditions existed at the take-off point in the upper downcomer barrel. However, unlike the other tests where blowdown was monitored, the measured IKP-4 concentrations increased by about 22% overall, rather than collapsing to low values. This change in observed behavior is believed to be caused by low levels of voidage at the IKP-4 sample take-off point, so that the effects of concentration during blowdown could be observed directly. Similar behavior to that described here can be inferred in earlier tests from the conductivity traces during blowdown following completion of the test, or from mass balance considerations.

Unlike earlier tests, blowdown did not cause any change in the observed carryover level. At all times, carryover of both lithium and potassium remained undetectable.

Operation at 102.5 in. Water Level

At 102.5 in. the behavior of the two model boiler sample lines was different. As in other tests at this level, the S-1 line showed little response to the SGTR injection, but rather it showed a progressive fall in tracer concentrations. As before, also the conductivity measured was essentially identical to that of the SORV condensate. Both results indicate that the S-1 line was sampling steam and that the change in tracer concentrations were due to the slow cleanup of contaminated surfaces exposed to steam. In contrast with this behavior, the IKP-4 line gave the response seen typically in tests at normal water level. Thus the lithium concentration only fell by the amount expected by sampling losses, while the potassium concentration and the conductivity increased at a constant rate during the SGTR injection. Further, there was little change on equilibration after the SGTR flow was halted. All this would indicate no loss of tracers by hideout, and clearly this is different from the behavior seen in tests at higher secondary pressures.

In this part of the test, the SORV condensate gave a similar response to that seen at normal water level, but with an enhanced initial burst of carryover. In this case, the maximum values observed were 1 ppb lithium and 60 ppb potassium, while the values towards the end of the SGTR injection were of the order of 0.2 ppb lithium or potassium. Estimates for the transient releases and for steady-state carryover and bypassing based on these figures are given in Section 7-3.

Test 15 - 10% SORV Flow, Blowdown from 442 in. to 48 in. and Operation with SGTR at Top of Tube Bundle at Four Water Levels with Dryer Bypassed (T-2050 - T-2054)

This test was a repeat of Test 8, but with the secondary separator vanes bypassed so that the effectiveness of the primary separator alone could be assessed. The test was again split into five separate sections: an initial blowdown phase when water level was reduced from 442 in. to 48 in. and then four short SGTR injections at water levels of 60 in., 100 in., 160 in. and 285 in. For each part of the test, the target initial steady-state conditions were as follows:

Plant Parameter	Desired Value
Primary pressure	1850 psia (127.6 bar)
Primary T_{hot}	580°F* (304°C*)
Primary flow rate	91 lbm/sec* (41.3 kg/s)
Secondary pressure	1080 psia (74.5 bar)
Saturation temperature	554°F (290°C)

*T_{hot} and primary flow could be adjusted as required to achieve the desired secondary pressure.

In the initial phase of the test, the model boiler was dosed with lithium hydroxide while at normal water level. The level dosed was inadvertently less than intended, but the lower concentration was accepted as it was expected that it would reduce the time taken to remove tracer contamination of the steam dome and steam line should carryover be increased with the dryer bypassed. Once the lithium concentration was known, the level was blown down. As in the other tests, the blowdown rate was controlled so that the level was reduced over a period of about 60 minutes. Data were collected over a period extending from 10 minutes before blowdown commenced until the level had stabilized at 48 in. As the tube bundle uncovered, the secondary pressure fell and the auxiliary feedwater flow had to be reduced to maintain the rate of change in water level.

After blowdown was complete, the system was allowed to equilibrate for about 80 minutes before the first SGTR injection was started. During this period, water level was raised to 60 in. and T_{hot} to 593°F (312°C), with maximum primary loop flow, in order to restore secondary pressure to the target level. During the first SGTR cycle at 60 in., data were collected for 5 minutes before initiating the SGTR, then during the 30 minutes of SGTR injection, a further 20 minutes of steady-state operation and finally during the level increase to 100 in. During this period, the auxiliary feedwater flow was adjusted as required, first to maintain water level and then to increase it to 100 in. This sequence differed from that used in the earlier tests in that the period between the SGTR injection and the level change was extended to 20 minutes in order to give a better separation between the bursts of carryover. For the remaining SGTR cycles, an identical sequence was followed, the only exception being that T_{hot} could be reduced to 580°F in all tests as sufficient water existed in the tube bundle at 100 in. and above to generate the required secondary pressure.

For all the five sections of the test, the model boiler void space was drained periodically before the test, the void space drain valve was kept closed during the individual tests and the SGTR line was warmed up before each SGTR injection. At all times, feedwater was supplied via the main feed system. In this system, there was a small leak at the feedline connection to the upper

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130

shell of the model boiler. The leak rate was 33 lbm/hr (about 4 gallon/hr). Additionally, the primary outlet thermocouple (T-1250) was found to be operating erratically and probably should be disregarded.

Figures 5-393 to 5-472 illustrate the performance of the relevant thermal-hydraulic parameters during the test. They are presented subdivided into the separate phases of the test in the following pages.

Chemical samples were collected for the entire duration of the test. As in Test 8, the results are subdivided into three major divisions, namely the blowdown phase, the SGTR injections at 60 in. and 100 in. and the SGTR injections at 160 in. and 285 in. Due to the duration of the test the sample line flow rates, particularly that of the IKP-4 line, fell during the test and had to be reset. Neither the drop in flow rate, nor the resetting of the flow rates are believed to have influenced the results significantly. The full results are summarized in Tables 5-29 and 5-30 and are shown in Figures 5-473 to 5-479.

Blowdown Phase (T-2050)

Before the blowdown phase, the model boiler was dosed with about 20 g lithium hydroxide to give an initial concentration of 8 ppm lithium. During blowdown, the measured concentrations fell on both the S-1 and IKP-4 sample lines. For the S-1 sample line the concentrations fell rapidly, but even at 160 in. the measured concentration was about 1.8 ppm lithium, indicating that 23% of the mass sampled was due to droplets of model boiler water. When the level fell below 150 in., the measured concentrations again collapsed to low values, eventually to 4 to 6 ppb lithium, suggesting that the line was now sampling only steam. The IKP-4 sample line showed a similar pattern of behavior, but once again the concentrations did not fall away as rapidly as did those on the S-1 sample line and the concentrations did not finally collapse to low values until the level had stabilized at 48 in. For both sample lines, the changes in potassium concentration paralleled those noted above for lithium.

131

At water levels > 130 in. carryover was not detectable. Based on a limit of detection of 0.2 ppb lithium and a model boiler water concentration of 8 ppm, the upper limit for carryover was ≤ 0.0025%. Below 130 in. carryover again increased, there being an initial peak in carryover as the bundle uncovered followed by a sustained increased level. Estimates of the quantity released during the initial transient and of carryover during subsequent steady-state operation are given in Section 7-3.

SGTRs at 60 in. and 100 in. (T-2051 and T-2052)

Before the SGTR phases of the test, the primary circuit was dosed to give a concentration of 53 ppm potassium. As the makeup tank nominally contained 50 ppm potassium the concentrations were expected to fall slightly; however, in practice the levels rose slightly over the complete test, indicating a slightly higher concentration in the makeup tank. As in previous tests, the lithium concentrations were low, 1.8 ppb initially. Unusually, the concentrations rose to 4.6 ppb by the end of the test, indicating that some contamination of the makeup tank had occurred.

The behavior of the two model boiler sample lines was again different during these SGTR injections at low level. As in the earlier tests, the S-1 sample line showed little response either to the SGTR flows or to the first level change, and only detected low concentrations of both lithium and potassium. In parallel with this behavior, the conductivity was essentially identical to that of the SORV condensate. Both effects indicate that the S-1 line was sampling steam, with very few droplets of model boiler water present. As the level was raised above about 140 in. during the second level change, the S-1 sample line recovered and again gave samples containing high concentrations of both lithium and potassium.

As in the earlier top break test, Test 8, the SGTR injection at 60 in. and the subsequent level change to 100 in. produced only a small response on the IKP-4 sample line. In this period the potassium concentration peaked at the end of the SGTR injection, at 12 ppm (cf 8 ppm in Test 8), but it then decayed to 6 ppm during the subsequent period of steady-state operation. Following the

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132

level change, the concentration at first rose to 57 ppm before finally stabilizing at about 16 to 20 ppm as the system equilibrated fully. Similar changes in lithium concentration were seen. Again, as in Test 8, the SGTR injection at 100 in. produced a large increase in conductivity and in both lithium and potassium concentrations. Here the potassium concentration again peaked at the end of the SGTR injection, at 400 ppm (cf 176 ppm in Test 8), but then fell to about 300 ppm during the subsequent period of steady-state operation. As the level was raised to 160 in., the concentration fell further to 200 ppm potassium. Once again the lithium concentration increased during the initial part of the SGTR injection to a stable value of 2 ppm, before falling during the level change to about 0.7 ppm lithium.

The behavior of the SORV condensate was again dominated by bursts of carryover during the SGTR injections and level changes. In the two SGTR injections, there were initial bursts of lithium carryover as the SGTR flows commenced, the maximum carryover observed being 25 ppb at 60 in. and 7 ppb at 100 in. In each case the carryover fell during the remainder of the SGTR injection and the subsequent steady-state operation. During the SGTR injection at 60 in., there was no corresponding burst in potassium carryover, instead carryover increased during the SGTR injection to reach a maximum value of 100 to 130 ppb which was maintained during the subsequent steady-state operation. In the following SGTR injection at 100 in., the potassium carryover was similar to that for lithium. In this case the initial peak was 1000 ppb potassium, but this fell to 120 to 150 ppb before rising again during steady-state operation. Unlike other tests of this type, the level changes produced smaller and less well-defined bursts of carryover. For potassium, the maximum carryover detected was 600 ppb for the 60 in. to 100 in. level change and 690 ppb for the 100 in. to 160 in. level change. The corresponding values for lithium were 2.5 to 1.7 ppb, respectively. The analysis of carryover and/or bypassing in this part of the test is given in Section 7-3.

As in other SGTR tests, the resistivity of the SORV condensate in this and the later stages of the test was dominated by the carryover of ammonia. Typically, during the SGTR injections the resistivity was 0.018 to 0.028 MΩ cm (≡ 36 to 56 μS/cm), corresponding to 15 to 31 ppm ammonia. At other times the

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resistivity varied from 0.6 to 1.8 MΩ cm (≡ 0.56 to 1.7 μS/cm), equivalent to 0.03 to 0.14 ppm ammonia. During steady-state operation, the variation in resistivity is believed in part to be due to poor mixing within the surge tank, but also to the refilling of the surge tank which took place during the test.

SGTRs at 160 in. and 285 in. (T-2053 and T-2054)

In the final two SGTR injections, both the S-1 and IKP-4 sample lines responded in a similar manner to that seen in Tests 8 and 9. At both water levels the S-1 sample line gave lower measured concentrations, with the difference being more pronounced at the lower level, and once again the conductivity trace at 160 in. for the S-1 line showed fairly large variations due to small changes in level.

During each SGTR injection, the lithium concentrations remained constant. On increasing the water level, the concentrations measured using the IKP-4 sample line fell as expected due to dilution, but this was not detected on the S-1 line where the effects of dilution were compensated for by an increase in the quantity of droplets sampled. For the IKP-4 sample line, the measured concentrations were about 0.7 ppm lithium at 160 in. and about 0.47 ppm at 285 in. As in the other SGTR tests, both the potassium concentration and the conductivity increased approximately linearly during the SGTR injections. At 160 in. the concentration fell significantly during the following period of steady-state operation, indicating incomplete mixing due to the poor recirculation rate, and then it fell again as the level was increased. At 285 in., there was little change in concentration following the SGTR injection. For the IKP-4 line, the change in potassium concentration was from 200 ppm to 360 ppm and then to 320 ppm at 160 in. and from about 205 ppm to 275 ppm at 285 in.

The response of the SORV condensate was essentially identical for both lithium and potassium, see Figure 5-479. In both cases the level of carryover decreased progressively throughout the period covered in this part of the test from the level initially caused on raising water level to 160 in. Superimposed on this general trend were three small bursts of carryover. Of these, two occurred at the start of each SGTR injection while the third occurred during steady-state operation preceding the level change. An analysis of this carryover behavior is also given in Section 7-3.

Test 16 - 10% SORV Flow, Blowdown from 442 in. to 57 in. and Operation with SGTR at Bottom of Tube Bundle at Four Water Levels with Dryer Bypassed (T-2061 - T-2065)

This test was a repeat of Test 9, but with the secondary separator vanes bypassed so that the effectiveness of the primary separator alone could be assessed. The test was again split into five separate sections: an initial blowdown phase when water level was reduced from 442 in. to 57 in. and then four short SGTR injections at water levels of 60 in., 105 in., 155 in. and 285 in. For each part of the test, the target initial steady-state conditions were as follows:

Plant Parameter	Desired Value
Primary pressure	1850 psia (127.6 bar)
Primary T_{hot}	580°F* (304°C*)
Primary flow rate	91 lbm/sec* (41.3 kg/s)
Secondary pressure	1080 psia (74.5 bar)
Saturation temperature	554°F (290°C)

*T_{hot} and primary flow could be adjusted as required to achieve the desired secondary pressure.

In the initial phase of the test, the model boiler was dosed with lithium hydroxide while at normal water level. Once the lithium concentration had been established, the level was reduced to 57 in. As in other tests, the blowdown rate was controlled so that the level was reduced over about

135

50 minutes. Data were collected over a period extending from 10 minutes before blowdown commenced until the level had stabilized at 57 in. As the tube bundle uncovered, the secondary pressure fell and the auxiliary feedwater flow had to be reduced to maintain the rate of change in water level.

After blowdown was complete, the system was allowed to equilibrate for about 75 minutes before the first SGTR injection was started. During this period, water level was raised to 60 in. and T_{hot} to 594°F (312°C), with maximum primary loop flow, in order to restore secondary pressure to the target level. For the first SGTR cycle at 60 in., data were collected for 5 minutes before initiating the SGTR, then during the 30 minutes of SGTR injection, a further 20 minutes of steady-state operation and, finally, during the level increase to 105 in. During this period, the auxiliary feedwater flow was adjusted as required, first to maintain water level and then to increase it to 105 in. The sequence was identical to that adopted in the previous test, with the extended period of steady-state operation designed to increase the separation between the bursts of carryover. For the remaining SGTR cycles an identical sequence was followed, the only exception being that T_{hot} could be reduced to 580°F in all tests as sufficient water existed in the tube bundle at 105 in. and above to generate the required secondary pressure.

For all the five sections of the test, the model boiler void space was drained periodically before the test, the void space drain valve was kept closed during the individual tests, and the SGTR line was warmed up before each SGTR injection. Throughout the testing, feedwater was supplied via the main feedwater system. In this line, there was a small leak at the feedline connection to the upper shell of the model boiler. The leak rate was 84.5 lbm/hr (10 gallon/hr). Additionally, the primary outlet thermocouple (T-1250) was found to be operating erratically and probably should be disregarded.

Figures 5-480 to 5-559 illustrate the performance of the relevant thermal-hydraulic parameters during the test. They are presented subdivided into the separate phases in the following pages.

Chemical samples were collected for the entire duration of the test. As in earlier tests, these results are subdivided into three major divisions, namely the blowdown phase, the SGTR injections at 60 in. and 105 in. and the SGTR injections at 155 in. and 285 in. Due to the duration of the test the sample line flow rates tended to fall as the test proceeded. This was particularly true of the IKP-4 sample line which had to be reset repeatedly. Neither the drop in flow rate, nor the resetting of the flows are believed to have affected most results, but the very low IKP-4 sample line flow rates which occurred during the blowdown phase did influence the measured concentrations. The full results are summarized in Tables 5-31 and 5-32 and are shown in Figures 5-560 to 5-566.

Blowdown Phase (T-2061)

Before the blowdown phase, the model boiler was dosed with about 100 g lithium hydroxide. After equilibration, the S-1 sample line indicated an initial concentration of 59 ppm lithium, while the IKP-4 line indicated only 51 ppm, both after dilution for analysis. The reason for this discrepancy, which was not observed on the undiluted samples analyzed for potassium, is not known. From calculations based on the mass of water in the model boiler, see Section 7-2, it is considered that the S-1 sample line gave the more representative result.

During blowdown, the measured concentrations fell on both the S-1 and IKP-4 sample lines. For the S-1 sample line the concentrations fell rapidly, but even at about 150 in. the measured concentration was 20 ppm lithium and 150 ppb potassium, indicating that even at this level about 34% of the mass sampled was due to droplets of model boiler water. When the level fell below 150 in., the measured concentrations collapsed to low values which eventually reached 20 to 40 ppb lithium, suggesting that the line was sampling only steam. The IKP-4 sample line showed a similar pattern of behavior, but once again the concentrations did not fall away as rapidly as did those on the S-1 sample line and the concentrations did not finally collapse to low values until the level had stabilized at 57 in. In addition, the results for this line were also affected by the very low sample line flow rates which occurred over the period 55 to 67 minutes. At these very low flow rates the results indicate that there was a change in the proportion of steam and water sampled from the two-phase mixture in the model boiler.

At water levels > 150 in., carryover was low. Based on the observed values of 0.2 to 0.6 ppb lithium and 0.4 to 1.2 ppb potassium and on model boiler water concentrations of 59 ppm lithium and 460 ppb potassium, carryover was 0.0003 to 0.001% (lithium) or 0.087 to 0.26% (potassium). The higher carryover indicated from potassium measurements in this test was influenced by slightly elevated background potassium concentrations associated with an offshore wind and rain during testing. Below about 100 in. carryover again increased. In this test there was no well defined peak as the bundle uncovered, instead maximum carryover occurred shortly after blowdown was complete, at 40 ppb lithium, before it decayed again to a sustained level of about 6 ppb lithium. Estimates of the quantity released during the transient and of carryover during subsequent steady-state operation are given in Section 7-3.

SGTRs at 60 in. and 105 in. (T-2062 and T-2063)

Before the SGTR phases of the test, the primary circuit was dosed to give a concentration of 53 ppm potassium. As the makeup tank contained approximately 60 ppm potassium, the concentration of the primary loop increased during the test. In contrast with this behavior, both the conductivity and the lithium concentrations fell, since the makeup tank contained less lithium and probably less ammonia than the primary loop. Similar behavior occurred in the later stages of the test.

The behavior of the two model boiler water sample lines was again different at low level. As in the other tests of this type, the S-1 sample line showed little response either to the SGTR flows or to the first level change, and only detected low concentrations of both lithium and potassium. Again, the conductivity was essentially identical to that of the SORV condensate. Both effects indicate that the S-1 line was sampling almost pure steam, with very few droplets of model boiler water present. As the level was raised above about 140 in. during the second level change, the S-1 line recovered and again gave samples containing high concentrations of both lithium and potassium.

As in the other bottom break test, Test 9, but in contrast with the top break tests, Tests 8 and 14, the IKP-4 sample line responded strongly to the SGTR flow during both SGTR injections. During the SGTR injection at 60 in. the potassium concentration increased to 380 ppm (cf 390 ppm in Test 9 and 8 or 12 ppm in the two top break tests), while at 105 in. it increased to 310 ppm (cf 280 ppm, Test 9; 176 to 400 ppm, top break tests). During steady-state operation, the concentrations fell to about 145 ppm at 60 in. and to about 250 ppm at 105 in., indicating that the model boiler water was poorly mixed during the SGTR injections. During the level change to 105 in. the measured concentrations unexpectedly increased. The reason for this is not known, but it could be due to incomplete equilibration during the preceding steady-state operation or possibly to a change in steam quality around the sample take-off point. A similar effect did not occur during the second level change after which the potassium concentration stabilized at about 250 ppm. Unlike other tests, the lithium concentration did not remain stable during this part of the test, instead it responded in a similar way to that for potassium, although on a very much reduced scale. Again, the reason for this behavior is unknown, but it must reflect changes in concentration and/or steam quality at the sample take-off point.

As in the other three tests of this type, the SORV condensate gave a complex response to both the SGTR injections and to the level changes. These consisted of large bursts of carryover at the start of the two level changes and of smaller bursts of carryover during the SGTR injections. In this, the test was similar to the earlier bottom break test, Test 9, but different from the two top break tests. As in other tests, the bursts in carryover did not decay fully before the next initiating event. For the level changes, the peak concentrations were 60 to 105 in., 80 ppb lithium and 1260 ppb potassium; 105 to 155 in., 50 ppb lithium and 1220 ppb potassium. During the SGTRs, in contrast with the earlier test with the dryer in operation, there were small peaks at the start of the SGTR flows, 20 ppb lithium and 15.6 ppb potassium at 60 in. and 20 ppb lithium and 760 ppb potassium at 105 in. However, for the

139

remainder of the SGTR injection at 60 in., the potassium carryover increased as it did in the other three tests to reach a maximum of 50 ppb at the end of the SGTR injection. At 105 in., unlike other tests, the potassium carryover remained high, about 600 ppb, throughout the SGTR injection and subsequent level change. Estimates of carryover and/or bypassing based on these values are given in Section 7-3.

As in the other tests, the resistivity of the SORV condensate was dominated by carryover of ammonia. Typically, the levels were 0.044 to 0.060 MΩ cm (16 to 23 μS/cm) during the SGTR injections and 0.06 to 0.11 MΩ cm (9 to 16 μS/cm) at other times. These correspond to 4 to 7.5 ppm and 1.6 to 4 ppm ammonia respectively. Similar levels were seen in the final stages of the test.

SGTRs at 155 in. and 285 in. (T-2064 and T-2065)

In the final two SGTR injections, both the S-1 and IKP-4 lines gave results similar to those seen in the other tests of this type. At both water levels, the S-1 lines gave lower measured results, particularly at 155 in., and again the conductivity trace of 155 in. for the S-1 line showed large variations due to small changes in water level.

During the SGTR injection at 285 in., the blowdown concentrations on both sample lines, as expected, remained constant; but at 155 in. the measured concentrations increased slightly. On increasing water level, the concentrations measured using the IKP-4 line fell, but this was not seen on the S-1 line. The latter effect must be because the effects of dilution are compensated for by a change in steam quality at the S-1 take-off point, but the cause of the effect during the SGTR at 155 in. is unknown. For the IKP-4 sample line, the measured concentrations were about 17 ppm lithium at 155 in. and 11 ppm at 285 in. As in the other SGTR tests, the potassium concentration and the conductivity increased approximately linearly during the SGTR injections. At 155 in. the concentration fell slightly during the following period of steady-state operation and then again as the level was increased. At 285 in. there was no change in concentration following the SGTR injection.

For the IKP-4 line the change in potassium concentration was from about 250 ppm to 325 ppm and then to 310 ppm at 155 in. and from 205 ppm to 285 ppm at 285 in.

The behavior of the SORV condensate was essentially identical for both lithium and potassium, see Figure 5-566. In both cases the level of carryover decreased progressively throughout the period covered in this part of the test from the level produced on raising water level to 155 in. Superimposed on this general trend were two (or possibly three) small bursts of carryover which were more clearly defined in the results for potassium. One of these bursts of carryover occurred at the start of the SGTR injection at 155 in. and a similar burst possibly occurred at the start of the SGTR injection at 285 in. The remaining burst was again associated with the level change, but, as in the previous test, it occurred immediately before the level change was carried out. An analysis of this behavior is given in Section 7-3.

TABLE 5-1

ANALYTICAL RESULTS, TEST 1 (T-1952)

Run Time (min)	Primary				Model Boiler								SORV Condensate		
					S-1				IKP-4						
	Li (ppb)	K (ppm)	pH	Conductivity (µS/cm)	Li (ppm)	K (ppm)	pH	Conductivity (µS/cm)	Li (ppm)	K (ppm)	pH	Conductivity (µS/cm)	Li (ppb)	K (ppb)	Resistivity (MΩ cm)
-60	-	-	-	240	-	-	-	290(f)	-	-	-	-	-	-	0.100
-50	-	-	-	240	-	-	-	365	-	-	-	-	-	-	0.101
-40	-	-	-	240	-	-	-	410	-	-	-	365	-	-	0.102
-30	-	-	-	240	-	-	-	410	-	-	-	400	-	-	0.102
-20	3.1	50	9.45	240	40	0.200	-	405	40	0.200	-	401	~0.2	2.0	0.102
-10	-	-	-	240	-	-	-	405	-	-	-	403	-	-	0.102
-5	3.1	49	-	240	38.5	0.200	9.3	405	40	0.200	-	405	~0	1.0	0.103
0	-	-	-	239	-	-	-	405	-	-	-	410	-	-	0.102
6	-	-	-	239	38	6	9.35	416	40	0.220	9.7	409	~0.2	1.8	0.100
11	-	-	-	238	37.5	10	9.35	439	40	4	9.65	417	~0	2.0	0.050
16	3.1	50	-	235	38	18	9.35	455	40	8	9.65	440	~0	0.8	0.041
31	-	-	-	239	37	41.5	9.45	528	39	32	9.7	506	~0.2	0.8	0.033
46	2.8	50	-	241	37	63	9.55	593	39	59	9.75	571	~0.2	1.1	0.033
61	-	-	-	245	38	90	9.6	664	38	81	9.8	633	~0.2	1.1	0.036
76	0.7	54	-	247	36	130	9.65	724	37	97	9.9	703	~0	1.1	0.037
91	-	-	-	249	35	160	9.7	795	36.5	142	9.95	768	~0.1	0.5	0.041
106	2.0	55	-	252	35	192	9.95	876	35	172	9.95	835	~0	1.0	0.044
121	1.8	54	9.10	255	34	236	9.8	945	35	208	10.0	895	~0.2	1.2	0.047
130	-	-	-	255	-	-	-	980	-	-	-	940	-	-	0.090
140	-	-	-	255	-	-	-	1005	-	-	-	980	-	-	0.114
150	-	-	-	255	-	-	-	1005	-	-	-	1010	-	-	0.106
160	-	-	-	255	-	-	-	1000	-	-	-	1020	-	-	0.104
170	-	-	-	255	-	-	-	995	-	-	-	1015	-	-	0.100
180	-	-	-	255	-	-	-	980	-	-	-	1010	-	-	0.120

Notes:
(a) SGTR extended from 1 to 120 minutes.
(b) Conductivity and resistivity data taken from the computer output for the period 0-120 minutes and from the recorder trace at other times.
(c) All SORV condensate analyses and lithium analyses on primary samples were carried out undiluted using the 0-20 ppb ranges. Precision ±0.1 to 0.3 ppb.
(d) All S-1 and IKP-4 samples and potassium analyses on primary samples analysed at 1:100 dilution using the 0-1000 ppb ranges, precision ±0.2 to 1.2 ppm, with the exception of some potassium analyses carried out at dilutions of 1:200 (S-1 samples @ 76 and 91 minutes, IKP-4 samples @ 91 and 105 munutes) and 1:400 (S-1 samples @ 105 and 120 minutes, IKP-4 sample @ 120 minutes).
(e) Make-up tank pre-test contained 77 ppm potassium, ~0.4 ppb lithium. The primary loop pre-test contained <5 ppb oxygen and 3.6 ppm hydrazine and the surge tank 3 ppm oxygen and 8 ppm hydrazine.
(f) Pre-dose value.

142

TABLE 5-2

SAMPLE LINE FLOW RATES, TEST 1 (T-1952)

Primary		Model Boiler				SORV Condensate	
		S-1		IKP-4			
Run Time (min)	Flow Rate (ml/min)	Run Time (min)	Flow Rate (ml/min)	Run Time (min)	Flow Rate (ml/min)	Run Time (min)	Flow Rate (ml/min)
-27	55	-25	154	-29	75	-	-
-13	54	-15	146	-13	70	-13	1277
-	-	10	134	12	64	-	-
26	48	24	138	25	64	23	1200
56	44	54	126	54	60	53	1200
80	44	77	126	78	62	77	1253
118	42	113	124	115	62	112	1200
125	40	123	124	124	62	122	1154

TABLE 5-3

ANALYTICAL RESULTS, TEST 2 (T-1958)

Run Time (min)	Primary				Model Boiler								SORV Condensate		
					S-1				IKP-4						
	Li (ppb)	K (ppm)	pH	Conductivity (µS/cm)	Li (ppm)	K (ppm)	pH	Conductivity (µS/cm)	Li (ppm)	K (ppm)	pH	Conductivity (µS/cm)	Li (ppb)	K (ppb)	Resistivity (MΩ cm)
-133	-	-	-	-	1(f)	4	7.0	-	-	-	-	-	~0	~0	-
-123	-	-	-	-	1(f)	2.5	7.0	-	-	-	-	-	~0	~0	-
-20	-	-	-	208	-	-	-	1463	-	-	-	1908	-	-	0.270
-10	-	-	-	208	-	-	-	1460	-	-	-	1902	-	-	0.290
0	1.7	53	9.5	207	50	1.5	11.60	1459	66	4	11.65	1908	~0	~0	0.303
15	-	-	-	208	50	1.5	11.50	1444	63	2.5	11.60	1975	~0	~0	0.300
30	1.7	55	-	208	50	3	11.50	1440	67	1	11.60	1932	~0	~0	0.298
35	-	-	-	208	48	3	11.35	1387	66	1	11.60	1890	~0.2	1.0	0.056
40	-	-	-	208	53	15	11.55	1560	77	12	11.70	2298	1.9	0.7	0.052
45	-	-	-	206	48	27	11.45	1492	68	26	11.50	2094	~0	~0	0.051
60	1.7	51	-	202	51	65	11.55	1730	66	72	11.70	2315	~0	~0	0.054
75	-	-	-	197	48	93	11.65	1941	62	102	11.50	2487	~0	~0	0.058
90	1.9	50	9.5	192	47	116	11.70	2135	64	154	11.70	2747	~0	~0.2	0.062
105	-	-	-	189	50	160	11.60	2361	62	195	11.80	3023	~0	~0.2	0.067
110	-	-	-	186	49	170	11.70	2480	64	210	11.80	3274	~0	0.7	0.068
115	-	-	-	185	47	190	11.70	2518	70	255	11.90	3901	1.9	5.6	0.072
120	1.3	52	-	185	50	210	11.50	2524	80	330	11.80	4577	0.65	4.0	0.074
125	-	-	-	183	52	230	11.70	2831	85	350	12.00	4795	~0.2	~0	0.075
135	-	-	-	180	54	260	11.90	3266	79	370	11.80	4739	0.65	4.5	0.078
142.5	-	-	-	179	53	275	11.80	3377	75	370	11.80	4717	0.5	1.25	0.081
150	1.0	47	-	178	48	265	11.80	3031	67	350	11.90	4180	0.5	0.3	0.083
155	-	-	-	177	45	265	11.80	3086	57	300	11.60	3666	0.5	0.7	0.084
160	-	-	-	175	44	260	11.25	3094	56	350	11.90	3696	~0	~0	0.086
165	-	-	-	175	42	250	11.80	2719	52	300	11.50	3369	0.4	0.7	0.088
175.5	-	-	-	173	37	230	11.60	2558	42	250	11.50	2954	~0.2	~0	0.228
180	1.0	46	9.15	172	36	220	11.40	2474	38	230	11.80	2679	~0	~0	0.249
195	-	-	-	171	33	220	11.45	2402	33	210	11.70	2454	~0	~0	0.230
205	-	-	-	170	-	-	-	2402	-	-	-	2450	-	-	0.220

Notes:
- (a) SGTR extended from 30 to 164 minutes.
- (b) Conductivity and resistivity data taken from the computer output for the period 0-196 minutes and from the recorder trace at other times.
- (c) All SORV condensate analyses and lithium analyses on primary samples carried out using the 0-20 ppb ranges. Precision ±0.1 to 0.3 ppb.
- (d) All other analyses were carried out using the 0-1000 ppb ranges, either after dilution by 1:100, 1:200 (lithium analyses IKP-4 sample @ 45 minutes, potassium analyses IKP-4 samples @ 45 and 60 minutes and the S-1 samples @ 60 and 75 minutes) or 1:1000 (potassium analyses on the IKP-4 or S-1 samples @ 60 and 75 minutes respectively).
- (e) Pre-test the surge tank contained 2 ppm oxygen and 10 ppm hydrazine, and the primary make-up tank 48 ppm potassium and ~3 ppm oxygen. Pre-test the model boiler contained <5 ppb oxygen and 0.01 ppm hydrazine, post-test the oxygen was ~250 ppb.
- (f) Pre-dose values.

TABLE 5-4

SAMPLE LINE FLOW RATES, TEST 2 (T-1958)

Primary		Model Boiler				SORV Condensate	
		S-1		IKP-4			
Run Time (min)	Flow Rate (ml/min)	Run Time (min)	Flow Rate (ml/min)	Run Time (min)	Flow Rate (ml/min)	Run Time (min)	Flow Rate (ml/min)
8	42	6	96	7	44	5	723
-	-	-	-	13	84	-	-
21	40	18	60	20	80	17	750
38	40	34	56	35	78	33	698
49	36	47	52	49	76	47	732
65	34	63	52	64	72	62	732
79	34	78	52	78	72	77	750
95	32	93	52	94	72	92	732
109	32	108	50	113	70	107	750
130	32	128	46	129	68	126	732
140	30	139	42	139	68	138	732
154	30	152	42	157	66	152	723
172	30	170	38	171	64	169	723
183	30	184	38	184	64	183	714

Notes: IKP-4 and S-1 flows adjusted after 12 and 14 minutes respectively.

TABLE 5-5

ANALYTICAL RESULTS, TEST 3 (T-1970)

Run Time (min)	Primary			Model Boiler						SORV Condensate		
				S-1			IKP-4					
	Li (ppb)	K (ppm)	Conductivity (μS/cm)	Li (ppm)	K (ppm)	Conductivity (μS/cm)	Li (ppm)	K (ppm)	Conductivity (μS/cm)	Li (ppb)	K (ppb)	Resistivity (MΩ cm)
-30	-	-	207	-	-	960	-	-	935	-	-	0.057
-20	-	-	207	-	-	935	-	-	910	-	-	0.061
-10	-	-	207	-	-	910	-	-	880	-	-	0.070
0	-	-	207	-	-	900	-	-	865	-	-	0.081
1	6.9	40	207	41.5	1.5	900	42	1.5	865	~0	~0	0.082
15	-	-	207	42	1	872	42	1.5	845	~0	~0	0.089
30	6.5	39	207	42	2	858	38	1	830	~0	~0	0.089
35	-	-	207	41	4	829	41.5	1	824	~0	~0	0.016
40	-	-	207	41	5	845	41.5	1	812	~0	~0	0.008
45	-	-	206	41.5	9	873	41	3	819	~0	1.0	0.006
60	6.2	38	207	41.5	18	940	41	12	894	~0	1.0	0.007
75	-	-	206	41.5	29	1000	41	23	957	~0	~0.2	0.007
90	5.4	37	206	41.5	39	1044	41	33	1008	~0	~0	0.007
105	-	-	206	41.5	51	1111	41	45	1060	~0	6.2	0.007
112	-	-	206	-	-	1137	-	-	1090	~0	~0.2	0.007
120	5.0	39	206	41.5	60	1161	41	54	1116	~0	~0	0.007
135	-	-	206	41.5	70	1226	41	65	1173	~0	~0	0.007
150	4.5	40	207	41	80	1265	41	75	1226	~0	~0.2	0.007
152.5	-	-	207	-	-	1297	-	-	1234	~0	~0.2	0.008
155	-	-	206	-	-	1301	-	-	1239	~0	~0	0.009
160	-	-	207	-	-	1281	-	-	1244	~0	~0.2	0.017
165	-	-	206	42	88	1261	41	80	1228	~0	~0	0.026
180	4.2	41	207	42	92	1251	41	81	1212	~0	~0	0.056
190	-	-	207	-	-	1290	-	-	1195	-	-	0.066
200	-	-	207	-	-	1170	-	-	1235	-	-	>>0.2
210	-	-	207	-	-	1060	-	-	1305	-	-	-

Notes:
(a) SGTR extended from 30 to 150 minutes.
(b) Conductivity and resistivity data taken from the computer output for the period 0-180 minutes and from the recorder traces at other times.
(c) All SORV condensate analyses and lithium analyses on primary samples were carried out using the 0-20 ppb ranges. Precision ±0.1 to 0.3 ppb.
(d) All other analyses, except where noted below, were carried out at a 1:100 dilution using the 0-1000 ppb ranges. Precision ±0.2 to 1.2 ppm.
(e) S-1 samples after 165 and 180 minutes were analysed at a 1:200 dilution.
(f) Pre-test the make-up tank contained ~40 ppm potassium and ~80 ppm hydrazine and the surge tank 3 ppm oxygen and 8 ppm hydrazine. Pre-test the model boiler contained <5 ppb oxygen and post test ~60 ppb oxygen. The primary loop contained <5 ppb oxygen and 2 ppm hydrazine.

TABLE 5-6

SAMPLE LINE FLOW RATES, TEST 3 (T-1970)

Primary		Model Boiler				SORV Condensate	
		S-1		IKP-4			
Run Time (min)	Flow Rate (ml/min)	Run Time (min)	Flow Rate (ml/min)	Run Time (min)	Flow Rate (ml/min)	Run Time (min)	Flow Rate (ml/min)
-28	52	-29	80	-29	62	-31	556
8	50	5	80	7	60	5	556
19	50	18	76	19	60	17	577
33	50	32	74	33	60	31	556
49	50	48	74	48	60	47	545
63	50	62	74	62	60	61	545
78	48	77	72	77	60	76	536
93	50	92	74	92	60	91	526
109	48	108	76	109	60	107	536
123	48	122	76	123	60	121	526
139	48	138	74	139	60	137	517
155	46	154	70	156	59	153	612
167	46	166	70	167	58	166	638
182	46	181	74	182	58	181	556

TABLE 5-7

ANALYTICAL RESULTS, TEST 4 (T-1982)

Run Time (min)	Primary			Model Boiler						SORV Condensate		
				S-1			IKP-4					
	Li (ppb)	K (ppm)	Conductivity (µS/cm)	Li (ppm)	K (ppm)	Conductivity (µS/cm)	Li (ppm)	K (ppm)	Conductivity (µS/cm)	Li (ppb)	K (ppb)	Resistivity (MΩ cm)
-30	-	-	205	-	-	-	-	-	860	-	-	0.174
-20	-	-	205	-	-	-	-	-	860	-	-	0.173
-10	-	-	205	-	-	845	-	-	860		-	0.173
0	-	-	205	-	-	847	-	-	862	-	-	0.172
2	1.6	45	202	41	2.5	847	42	2.0	862	~0	~0	0.172
15	-	-	205	42	3.5	848	44	1.5	864	0.4	~0	0.171
30	1.6	47	205	42	1.5	850	44	1.5	869	0.4	0.4	0.173
35	-	-	205	42	2.0	839	42	1.0	869	0.6	0.4	0.027
40	-	-	202	38	5.0	851	42	2.5	872	0.3	~0.2	0.016
45	-	-	208	42	8.5	858	42	5.0	875	~0	~0	0.013
60	1.6	47.5	212	42	20	907	41	15	918	~0	~0	0.011
75	-	-	212	42	31	981	41	25	981	~0	0.4	0.010
90	1.2	47	211	42	42	1028	41	35	1040	~0	~0.2	0.010
105	-	-	212	41	52	1096	41.5	47	1117	~0	~0.2	0.010
120	1.4	46	212	41	63	1157	41	58	1183	~0	~0	0.010
135	-	-	212	40	73	1206	43	74	1231	~0	~0	0.010
150	1.0	43	211	40	84	1261	41	77	1286	~0	~0.2	0.010
165	-	-	210	40	85	1270	42	88	1311	~0	~0	0.086
180	2.0	43	210	41	88	1292	40	83	1312	~0.2	~0	0.188
190	-	-	210	-	-	1280	-	-	1335	-	-	0.182
200	-	-	210	-	-	1050	-	-	1345	-	-	>>0.2

Notes:
(a) SGTR extended from 30 to 150 minutes.
(b) Conductivity and resistivity data taken from the computer output for the period 0-180 minutes and from the recorder traces at other times.
(c) All SORV condensate analyses and lithium analyses on primary samples were carried out using the 0-20 ppb ranges. Precision ±0.1 to 0.3 ppb.
(d) All other analyses carried out at a 1:100 dilution using the 0-1000 ppb ranges. Precision ±0.2 to 1.2 ppm.
(e) Pre-test the make-up tank contained 40 ppm potassium, 3 ppm oxygen and 8 ppm hydrazine, and the surge tank contained 3 ppm oxygen and 4 to 5 ppm hydrazine. Pre-test the model boiler contained <5 ppb oxygen, post test the level was ~90 ppb. The primary loop contained <5 ppb oxygen and 0.4 ppm hydrazine.

TABLE 5-8

SAMPLE LINE FLOW RATES, TEST 4 (T-1982)

Primary		Model Boiler				SORV Condensate	
		S-1		IKP-4			
Run Time (min)	Flow Rate (ml/min)	Run Time (min)	Flow Rate (ml/min)	Run Time (min)	Flow Rate (ml/min)	Run Time (min)	Flow Rate (ml/min)
-12	58	-13	90	-12	74	-14	588
4	57	3	87	4	74	2	600
18	56	16	84	17	72	16	588
33	56	31	84	32	69	31	588
48	54	46	84	47	66	46	556
63	55	62	82	63	66	61	577
78	56	77	82	77	66	76	545
93	56	92	81	92	64	91	484
-	-	-	-	-	-	93	492
108	56	106	80	107	64	106	526
123	58	121	78	123	68	121	488
138	60	137	79	137	66	136	484
154	60	152	77	153	62	151	545
168	58	167	74	167	60	166	500
183	59	181	72	182	56	181	500

Note: The SORV condensate sample line tended to airlock due to insufficient back pressure in the line to the SORV collection tank.

TABLE 5-9

ANALYTICAL RESULTS, TEST 5 (T-1972)

Run Time (min)	Primary			Model Boiler						SORV Condensate		
				S-1			IKP-4					
	Li (ppb)	K (ppm)	Conductivity (µS/cm)	Li (ppm)	K (ppm)	Conductivity (µS/cm)	Li (ppm)	K (ppm)	Conductivity (µS/cm)	Li (ppb)	K (ppb)	Resistivity (MΩ cm)
-30	-	-	218	-	-	930	-	-	925	-	-	0.015
-20	-	-	218	-	-	922	-	-	910	-	-	0.015
-10	-	-	218	-	-	917	-	-	900	-	-	0.015
0	-	-	218	-	-	913	-	-	892	-	-	0.014
1	3.5	41	218	45	5	912	45	3	892	~0	~0	0.015
15	3.7	41	216	45.5	6.5	909	45	1	887	~0	~0	0.014
30	3.7	41	218	46	6.5	910	45	2	890	~0	~0	0.014
35	-	-	217	46	3.5	895	45	1	887	~0	~0	0.009
40	-	-	218	45.5	5	897	45	3	884	~0	~0	0.005
45	-	-	217	45	5	898	44	2.5	884	~0	~0.2	0.005
60	3.5	41	216	43	9	902	44	6.5	889	~0	0.5	0.005
75	-	-	216	43	14	904	43	11	891	~0	0.6	0.004
90	3.5	40	216	42.5	17	906	47	16	894	~0	0.5	0.004
105	-	-	216	39	20	903	40	18.5	892	~0	0.5	0.004
120	3.5	41	216	39	21	900	39	21.5	889	~0	~0.2	0.004
135	-	-	216	39	28.5	891	38	25	881	~0	~0.2	0.004
150	3.0	40	216	38	30	883	36	29	874	~0	0.5	0.004
165	-	-	216	39	30.5	894	36.5	31	885	~0	0.4	0.005
180	3.0	38.5	216	37	30	879	36	31	870	~0	~0	0.006
190	-	-	216	-	-	865	-	-	865	-	-	0.008
200	-	-	216	-	-	960	-	-	865	-	-	0.010
210	-	-	216	-	-	1035	-	-	880	-	-	0.012

Notes:
(a) SGTR extended from 30 to 150 minutes.
(b) Conductivity and resistivity data taken from the computer output for the period 0-180 minutes and from the recorder trace at other times.
(c) All SORV condensate analyses and lithium analyses on primary samples were carried out using the 0-20 ppb ranges. Precision ±0.1 to 0.3 ppb.
(d) All other analyses were carried out at a 1:100 dilution using the 0-1000 ppb range. Precision ±0.2 to 1.2 ppm.
(e) Pre-test the make-up tank contained 40 ppm potassium, 2 ppm oxygen and 38 ppm hydrazine and the surge tank contained 1 ppm oxygen and 45 ppm hydrazine. The model boiler contained <5 ppb oxygen and the primary loop <5 ppb oxygen and 13 ppm hydrazine.

TABLE 5-10

SAMPLE LINE FLOW RATES, TEST 5 (T-1972)

Primary		Model Boiler				SORV Condensate	
		S-1		IKP-4			
Run Time (min)	Flow Rate (ml/min)	Run Time (min)	Flow Rate (ml/min)	Run Time (min)	Flow Rate (ml/min)	Run Time (min)	Flow Rate (ml/min)
-11	62	-12	80	-12	68	-13	714
3	62	3	82	3	66	2	732
18	62	17	82	17	68	16	714
32	62	31	81	32	69	31	732
48	62	47	82	47	68	46	698
64	60	63	83	63	69	62	667
79	60	77	83	78	70	77	667
93	62	91	83	93	69	91	667
108	63	107	83	107	69	106	625
123	62	122	84	122	69	121	638
138	62	136	84	137	69	136	652
153	64	152	83	153	68	152	682
167	62	166	82	167	68	165	674
183	63	182	82	183	66	182	698

TABLE 5-11

ANALYTICAL RESULTS, TEST 6 (T-1957)

Run Time (min)	Model Boiler				SORV Condensate	
	S-1			IKP-4		
	Li (ppm)	pH	Conductivity (µS/cm)	Conductivity (µS/cm)	Li (ppb)	Resistivity (MΩ cm)
-323	0.500(b)	-	-	-	-	-
-254	130(c)	11.5	-	-	-	-
-131	96(c)	-	-	-	-	-
- 50	-	-	3130	3130	-	0.155
- 40	-	-	3060	3170	-	0.155
- 30	-	-	2870	3180	-	0.155
- 20	-	-	2830	3130	-	0.156
- 10	-	-	2820	3060	-	0.156
2	94	11.85	2802	2947	0.9	0.139
10	-	-	2767	2816	0.8	0.122
22	93	11.85	2692	2726	0.6	0.122
32	91	11.85	2619	2619	0.4	0.122
42	89	11.8	2562	2511	0.5	0.122
52	88	11.8	2518	2438	0.5	0.123
62	87	11.8	2487	2384	0.5	0.123
72	86	11.8	2420	2327	0.5	0.123
82	85	11.0	2338	2204	0.5	0.122
90	83	11.75	2281	2130	0.5	0.123
95	82	11.75	2216	2089	0.5	0.122
100	82	11.8	2156	2043	0.5	0.123
105	78	11.8	2151	1989	1.0	0.171
110	-	-	2281	1989	-	0.094
120	-	-	1850	2350	-	0.220

Notes:
- (a) Conductivity and resistivity data taken from the computer output for the period 0-110 minutes and from the recorder trace at other times.
- (b) Pre-dose value, measured undiluted 0-1000 ppb range.
- (c) Diluted 1:1000, measured on 1-1000 ppb range, precision ±2 to 12 ppm.
- (d) All S-1 samples (except where noted) diluted 1:100 and measured on 1-1000 ppb range. Precision ±0.2 to 1.2 ppm.
- (e) All SORV condensate samples measured undiluted on 0-20 ppb range. Precision ±0.1 to 0.3 ppb.

TABLE 5-12

SAMPLE LINE FLOW RATES, TEST 6 (T-1957)

Model Boiler				SORV Condensate	
S-1		IKP-4			
Run Time (min)	Flow Rate (ml/min)	Run Time (min)	Flow Rate (ml/min)	Run Time (min)	Flow Rate (ml/min)
4	63	4	46	4	714
18	62	-	-	18	732
34	62	-	-	33	741
44	62	-	-	44	732
53	62	-	-	52	750
63	64	-	-	62	732
74	60	-	-	74	741
84	60	-	-	84	732
95	60	-	-	95	750

TABLE 5-13

ANALYTICAL RESULTS, TEST 7 (T-1966)

Run Time (min)	Model Boiler						SORV Condensate	
	S-1			IKP-4				
	Li (ppm)	pH	Conductivity (µS/cm)	Li (ppm)	pH	Conductivity (µS/cm)	Li (ppb)	Resistivity (MΩ cm)
-40	-	-	94	-	-	50	-	0.132
-30	-	-	90	-	-	43	-	0.137
-28	10(e)	9.2	90	-	-	45	~0	-
-20	-	-	760	-	-	210	-	0.137
-10	-	-	1130	-	-	650	-	0.133
0	-	-	909	-	-	785	0.8	0.133
2	50	11.0	860	51	10.7	762	-	0.133
5	50	11.1	802	50	11.1	711	0.6	0.135
10	48	11.0	725	46	11.0	622	0.8	0.140
15	46	11.0	656	45	10.9	555	2.0	0.140
20	43	10.8	571	42	10.9	499	~0.2	0.133
25	42	10.6	489	39	10.6	433	~0.2	0.130
30	40	10.5	424	36	10.5	372	~0.2	0.130
35	38	-	370	31	10.3	323	~0.2	0.128
40	33	-	310	28	10.3	286	~0.2	0.128
45	28	9.8	271	25	10.2	249	~0	0.128
50	25	10.1	240	23	9.9	217	~0.2	0.127
55	21	9.9	192	20	9.8	189	50	0.134
60	9	9.9	99	18	9.8	159	210	0.129
61	-	-	87	-	-	152	80	0.136
63	-	-	91	-	-	131	20	0.134
65	11	8.6	95	9	9.7	109	4.2	0.127
70	9	9.5	93	7	9.3	76	2.4	0.125
75	9	9.2	89	7	9.2	72	1.2	0.123
80	9	9.5	82	7	8.9	69	0.4	0.125
85	8	9.2	77	6	9.0	66	0.6	0.123
95	7	9.3	69	5	9.0	62	0.4	0.135
105	7	9.2	66	5	9.1	61	0.6	0.130
115	7	9.2	65	5	8.8	60	~0	0.138
120	6	8.9	69	5	9.1	60	~0	0.139
130	-	-	66	-	-	59	-	0.140
140	-	-	7	-	-	186	-	0.307

Notes:
(a) Conductivity and resistivity data taken from the computer output, except for the period before the test commenced when it was estimated from the recorder trace.
(b) All S-1 and IKP-4 samples analysed at 1:100 dilution on 0-1000 ppb range. Precision ±0.2 to 1.2 ppm.
(c) All SORV condensate samples, except at 55 and 60 minutes, analysed undiluted on 0-20 ppb range. Precision ±0.1 to 0.3 ppb. Samples at 55 and 60 minutes analysed on 0- 1000 ppb range. Precision ±2 to 12 ppb.
(d) Before the test the S-1 sample contained <5 ppb oxygen, <0.1 ppm ammonia and 0.01 ppm hydrazine. After the tests S-1 contained ~100 ppb oxygen. The surge tank contained 3 ppm oxygen and 5 ppm hydrazine. The model boiler void space contained ~1 ppm lithium ~30 minutes before the test commenced and 8 ppm lithium after ~75 minutes.
(e) Before the second addition of lithium hydroxide.

TABLE 5-14

SAMPLE LINE FLOW RATES, TEST 7 (T-1966)

Model Boiler				SORV Condensate	
S-1		IKP-4			
Run Time (min)	Flow Rate (ml/min)	Run Time (min)	Flow Rate (ml/min)	Run Time (min)	Flow Rate (ml/min)
4	74	5	46	3	698
17	76	18	46	16	714
25	74	29	46	27	698
39	76	41	48	38	714
48	76	49	48	47	732
66	76	67	48	65	698
77	75	78	49	75	682
89	76	90	50	88	732
107	78	107	52	106	750
122	78	122	52	121	750

TABLE 5-15

ANALYTICAL RESULTS, TEST 8 (T-1975 to T-1979)

Run Time (min)	Primary			Model Boiler						SOHV Condensate		
				S-1			IKP-4					
	Li (ppb)	K (ppm)	Conductivity (μS/cm)	Li (ppm)	K (ppm)	Conductivity (μS/cm)	Li (ppm)	K (ppm)	Conductivity (μS/cm)	Li (ppb)	K (ppb)	Resistivity (MΩ cm)
-30	-	-	161	-	-	806	-	-	840	-	-	0.107
-20	-	-	161	-	-	800	-	-	830	-	-	0.110
-10	-	-	161	-	-	795	-	-	805	-	-	0.112
0	-	-	161	-	-	791	-	-	792	-	-	0.115
1	-	-	161	-	-	786	-	-	791	~0	-	0.116
2	-	-	161	50	0.220	784	50	-	786	-	-	0.116
5	-	-	162	50	-	776	50	0.210	779	~0	-	0.117
10	-	-	161	50	-	765	50	-	766	~0.2	-	0.118
15	-	-	162	45	-	659	49	-	748	~0.1	-	0.119
20	-	-	163	35	-	489	47	-	704	~0.2	-	0.116
25	-	-	162	26	-	346	43	-	616	~0.2	-	0.115
30	-	-	162	21	-	268	36	-	508	~0.2	-	0.117
35	-	-	162	16	-	208	30	-	400	~0	-	0.117
40	-	-	162	12	-	131	26	-	313	~0.2	-	0.127
45	-	-	163	0.960	-	17	18	-	208	25.8	-	0.116
50	-	-	163	0.380	-	11	10	-	116	10.0	-	0.113
55	-	-	163	0.190	-	10	5	-	58	3.2	-	0.109
60	-	-	162	0.115	-	9	5	-	59	8.4	-	0.108
65	-	-	163	0.100	-	9	3.5	-	45	6.4	-	0.120
70	-	-	163	0.080	-	9	2	-	25	5.6	-	0.128
75	-	-	163	0.070	-	9	0.820	-	13	5.6	-	0.136
95	-	-	163	0.050	-	8	0.230	-	10	4.0	-	0.134
125	-	-	195	0.040	-	8	0.265	-	10	4.9	-	0.134
165	-	-	195	0.045	-	11	0.265	-	14	6.0	-	0.098
182	0.5	52	195	-	0.080	15	0.260	0.010	21	10	0.7	0.077
187	0.4	52	196	0.040	0.040	23	0.230	0.010	23	400	4.2	0.046
195	0.4	52	195	0.025	0.090	35	0.260	0.020	25	30	60	0.030
200	0.5	52	194	0.130	0.150	29	1	0.970	42	11.0	30	0.042
215	~0.2	53	201	0.050	0.150	9	1.5	8	73	40	90	0.117
230	-	-	200	0.025	0.070	7	1.5	2.5	36	16.0	50	0.140
241	0.4	53	200	0.010	0.025	7	0.960	1.5	22	8.0	25	0.144
245	-	-	199	0.010	0.025	7	0.750	1	17	7.0	20	0.142
250	-	-	200	0.010	0.070	26	0.580	1	14	40	180	0.040
260	-	-	199	0.270	1.5	32	1	20	87	14	140	0.040
270	0.3	53	197	0.160	0.650	27	2	67	254	6.9	150	0.042
278	-	-	196	-	-	7	-	-	626	9.2	1500	0.126
279	-	-	197	0.040	0.560	7	5	176	659	-	-	0.131
295	-	-	196	9	100	425	9	106	410	6.0	50	0.148
311	-	-	196	-	-	315	-	-	470	2.7	20	0.133
312	~0.2	53	196	11	110	300	6	68	475	-	-	0.138

TABLE 5-15 (CONTINUED)

ANALYTICAL RESULTS, TEST 8 (T-1975 to T-1979)

Run Time (min)	Primary			Model Boiler						SORV Condensate		
				S-1			IKP-4					
	Li (ppb)	K (ppm)	Conductivity (µS/cm)	Li (ppm)	K (ppm)	Conductivity (µS/cm)	Li (ppm)	K (ppm)	Conductivity (µS/cm)	Li (ppb)	K (ppb)	Resistivity (MΩ cm)
326	-	-	195	7	78	298	11	116	466	2.0	18.9	0.131
330	-	-	195	8	84	359	10	106	449	2.0	22	0.118
335	~0.2	53	196	7	86	328	9.5	108	440	1.8	14.4	0.044
345	-	-	195	7	98	388	12	146	586	1.4	5.2	0.043
355	-	-	194	7	120	462	13	184	723	1.2	4.0	0.044
365	0.5	53	191	6	110	452	12	200	813	0.8	7.0	0.123
390	-	-	192	5	85	340	6	120	470	0.8	1.5	0.136
406	0.4	51	192	5	89	341	6	120	451	0.5	0.8	0.155
410	-	-	191	5	94	352	7	120	449	0.8	0.5	0.159
415	-	-	191	6	97	368	7	124	457	0.5	20	0.061
425	-	-	191	5	100	423	7	136	503	0.8	2.0	0.055
435	0.4	52	190	5	130	482	7	156	575	0.5	1.7	0.058
445	-	-	190	5	120	495	7	170	630	0.4	1.0	0.146
460	0.4	53	190	5	130	490	7	166	605	0.3	1.4	0.168
470	-	-	190	-	-	480	-	-	630	-	-	0.158
480	-	-	190	-	-	330	-	-	610	-	-	0.140
490	-	-	190	-	-	290	-	-	400	-	-	0.084

Notes:
(a) SGTRs extended from 185 to 198, 245 to 270, 330 to 355 and 410 to 435 minutes, blowdown from 10 to 55 minutes.
(b) Conductivity and resistivity data taken from the computer outputs for the periods 0 to 60, 180 to 225, 240 to 285, 325 to 370 and 405 to 435 minutes, and from the recorder trace at other times.
(c) All lithium analyses on SORV condensate and primary samples, except where noted below, were carried out using the 0-20 ppb range. Precision ±0.1 to 0.3 ppb. Potassium analyses on SORV condensate samples taken after 182, 188, 326, 365 to 410 and 425 to 460 minutes were also analysed using this range. Potassium analyses on SORV condensate samples taken after 330 to 355 and 415 minutes were analysed using a 0-40 ppb range.
(d) All other analyses were carried out using the 0-1000 ppb ranges, either undiluted (all other SORV condensate samples, S-1 samples (lithium 45 to 279 minutes, potassium up to 279 minutes) and IKP-4 samples (lithium 75 to 195 and 241 to 250 minutes, potassium up to 200 minutes), diluted 1:100 (primary samples for potassium, S-1 samples (lithium 1 to 40 and 295 to 460 minutes, potassium 260, 326 to 345 and 390 to 415 minutes) and IKP-4 samples (lithium 200 to 230 and 260 to 460 minutes, potassium 215 to 270 and 312 minutes), 1:200 (IKP-4 samples (potassium 278 to 295, 326 to 355 and 390 to 460 minutes) or 1:1000 (S-1 samples (potassium 295, 312, 355, 365 and 425 to 460 minutes) and IKP-4 samples (potassium 365 minutes).
(e) Pre-test the make-up tank contained 46 ppm potassium, 2 ppm oxygen and 12 ppm hydrazine, the surge tank 3 ppm oxygen and 1.6 ppm hydrazine, the primary loop <5 ppb oxygen and 8 ppm hydrazine and the model boiler <5 ppb oxygen and 0.01 ppm hydrazine.

TABLE 5-16

SAMPLE LINE FLOW RATES, TEST 8 (T-1975 to T-1979)

Primary		Model Boiler				SORV Condensate	
		S-1		IKP-4			
Run Time (min)	Flow Rate (ml/min)	Run Time (min)	Flow Rate (ml/min)	Run Time (min)	Flow Rate (ml/min)	Run Time (min)	Flow Rate (ml/min)
-	-	3	80	4	84	3	600
-	-	16	68	17	84	16	577
-	-	31	70	32	80	31	600
-	-	46	68	46	68	45	556
-	-	62	64	62	64	61	484
-	-	76	63	76	69	78	68
99	50	97	66	98	68	96	769
166	46	166	80	167	50	165	833
197	36	197	84	197	42	195	811
217	34	216	82	217	36	216	833
220	114	-	-	220	66	-	-
233	110	232	82	232	48	231	811
254	90	252	82	253	49	252	769
270	86	272	80	272	48	271	811
300	83	298	79	299	49	298	833
333	78	332	80	333	54	331	833
348	70	346	81	347	54	345	833
358	68	357	82	357	52	356	811
368	67	367	80	367	52	366	833
393	64	391	78	392	52	391	833
412	64	408	76	407	52	408	769
418	63	417	80	418	53	416	811
428	61	427	79	428	53	426	833
440	60	439	75	440	52	439	833
463	59	462	72	462	54	461	833

Notes:
(a) Blowdown commenced at 10 minutes, SGTRs at 185, 245, 330 and 410 minutes.
(b) Primary and IKP-4 flow rates increased after 219 minutes.
(c) SORV condensate flow failed after 70 minutes due to airlocking. Flow re-established after 90 minutes by increasing the back pressure in the line to the SORV collection tank.

TABLE 5-17

ANALYTICAL RESULTS, TEST 9 (T-1988 to T-1992)

Run Time (min)	Primary			Model Boiler									SORV Condensate		
				S-1			IKP-4			Blowdown					
	Li (ppb)	K (ppm)	Conductivity (µS/cm)	Li (ppm)	K (ppm)	Conductivity (µS/cm)	Li (ppm)	K (ppm)	Conductivity (µS/cm)	Li (ppm)	K (ppm)	Conductivity (µS/cm)	Li (ppb)	K (ppb)	Resistivity (MΩ cm)
-20	-	-	172	-	-	1020	-	-	1055	-	-	-	-	-	0.094
-10	-	-	172	-	-	985	-	-	1060	-	-	-	-	-	0.094
0	-	-	172	-	-	962	-	-	1025	-	-	-	-	-	0.094
2	-	-	172	58	-	942	65	-	1018	58	-	-	-0	-	0.094
10	-	-	172	58	-	913	65	-	981	63	-	-	0.3	-	0.093
15	-	-	172	52	-	858	64	-	953	65	-	-	-0.2	-	0.093
25	-	-	172	30	-	381	54	-	749	56	-	-	0	-	0.091
30	-	-	170	20	-	224	42	-	571	52	-	-	1.1	-	0.098
35	-	-	170	6	-	64	40	-	440	35	-	-	5.2	-	0.093
40	-	-	170	2	-	28	18	-	235	10	-	-	11.6	-	0.090
45	-	-	170	1	-	17	10	-	125	5	-	-	120	-	0.088
50	-	-	172	0.450	-	11	7	-	100	2	-	-	15.3	-	0.086
55	-	-	170	0.260	-	11	6	-	86	0.970	-	-	3.5	-	0.084
60	-	-	173	0.170	-	12	4	-	70	0.860	-	-	14.7	-	0.077
70	-	-	172	0.130	-	11	3	-	42	0.360	-	-	14.1	-	0.087
80	-	-	172	0.110	-	11	0.450	-	26	0.190	-	-	13.0	-	0.086
100	-	-	172	0.100	-	12	0.450	-	32	0.020	-	-	16.7	-	0.084
120	-	-	172	0.080	-	11	0.280	-	25	0.110	-	-	10.2	-	0.086
135	4.8	45	172	0.080	2	12	0.480	3	30	0.100	3	-	10.0	0.7	0.084
140	4.8	45	172	0.070	2	12	0.400	2	30	0.100	1.5	-	9.4	0.8	0.087
145	-	-	172	0.080	4	32	0.460	5	31	0.100	1	-	9.2	15.0	0.031
150	4.6	47	170	0.080	2	37	0.960	70	230	0.100	1	-	9.4	20	0.030
160	4.6	45	170	0.060	2	37	1	198	703	0.110	4	-	3.2	25	0.031
170	-	-	169	0.050	2	12	1	390	1069	0.120	14	-	2.9	50	0.094
185	-	-	168	0.050	4	11	1	120	390	0.100	14	-	60	980	0.088
210	4.2	44	167	0.050	2	11	3	38	168	0.050	5	-	6.3	180	0.091
215	-	-	167	0.045	1	11	2.5	33	143	0.470	6	-	5.3	120	0.089
220	4.0	44	167	0.040	1	26	1.5	23	111	0.450	5	-	4.1	340	0.034
225	-	-	167	0.030	1.5	33	1.5	46	185	0.390	5	-	2.9	150	0.033
235	-	-	166	0.030	1.5	31	1.5	120	416	0.230	2.5	-	5.2	750	0.033
245	3.7	44	163	0.030	2	16	5	280	900	0.140	4	-	1.5	110	0.092
260	3.5	44	163	14	80	360	20	130	610	0.200	7	-	20	350	0.094
305	3.5	43	162	16	84	401	27	130	669	13	70	-	10.4	80	0.095
310	-	-	162	15	80	356	26	126	653	12	65	-	10.0	70	0.095
315	-	-	162	14	78	370	26	128	650	13	73	-	8.6	60	0.041

TABLE 5-17 (CONTINUED)

ANALYTICAL RESULTS, TEST 9 (T-1988 to T-1992)

Run Time (min)	Primary			Model Boiler									SORV Condensate		
				S-1			IKP-4			Blowdown					
	Li (ppb)	K (ppm)	Conductivity (μS/cm)	Li (ppm)	K (ppm)	Conductivity (μS/cm)	Li (ppm)	K (ppm)	Conductivity (μS/cm)	Li (ppm)	K (ppm)	Conductivity (μS/cm)	Li (ppb)	K (ppb)	Resistivity (MΩ cm)
320	3.2	44	162	10	67	356	25.5	140	679	12	64	-	7.5	60	0.031
330	3.0	44	174	10	89	390	25	166	779	14	80	-	6.0	50	0.026
340	3.0	43	177	15	130	519	25	192	887	13	90	-	4.1	30	0.100
355	2.9	43	177	11	98	470	16	130	570	16	134	-	2.3	25	0.094
385	2.9	43	177	11	97	388	15	124	547	15	126	-	1.1	7.5	0.094
390	-	-	177	11	98	388	15	124	541	15	124	-	1.1	6.2	0.095
395	2.9	40	177	11	100	401	15	126	547	15	124	-	1.1	5.9	0.030
400	-	-	175	11	112	425	15	130	565	15	122	-	1.0	4.7	0.027
410	2.5	43	173	11	122	468	15	150	626	15	126	-	0.8	4.2	0.029
420	2.2	43	172	11	134	510	15	166	670	15	144	-	0.8	2.2	0.100
435	2.2	42	171	11	132	510	15	166	690	15	160	-	0.6	2.1	0.096
445	-	-	171	-	-	510	-	-	690	-	-	-	-	-	0.095

Notes:
(a) SGTRs extended from 140 to 165, 215 to 240, 310 to 335 and 390 to 415 minutes, blowdown from 10 to 55 minutes.
(b) Conductivity and resistivity data taken from the computer outputs for the periods 0 to 70, 135 to 185, 210 to 255, 305 to 355 and 385 to 420 minutes and from the recorder trace at other times.
(c) All SORV condensate samples, except as noted below, and all lithium analyses on primary samples analysed using the 0-20 ppb ranges. Precision ±0.1 to 0.3 ppb.
(d) All other samples analysed using the 0-1000 ppb ranges at a dilution of 1:100, precision ±0.2 to 1.2 ppm, except for the following. No dilution, lithium analyses on SORV condensate samples at 45,185 and 250 minutes, S-1 samples (50 to 245 minutes) IKP-4 samples (80 to 150 minutes) and blowdown samples. (55 to 250 minutes) plus potassium analyses on SORV condensate samples from 150 to 355 minutes. 1:200 dilution, potassium analyses on S-1 samples (340, 400 to 435 minutes), IKP-4 (160, 185, 235 and 260 to 435 minutes) and blowdown (355 to 435 minutes). 1:1000 lithium, potassium analyses on IKP-4 samples at 170 and 245 minutes.
(e) A primary make-up tank sample taken at 425 minutes contained 42 ppm potassium and ~0 ppb lithium. Pre-test the make-up tank contained 39 ppm potassium and ~2 ppm hydrazine and the surge tank 2 ppm oxygen and 6 ppm hydrazine.

TABLE 5-18

SAMPLE LINE FLOW RATES, TEST 9 (T-1988 to T-1992)

Primary		Model Boiler						SORV Condensate	
		S-1		IKP-4		Blowdown			
Run Time (min)	Flow Rate (ml/min)	Run Time (min)	Flow Rate (ml/min)	Run Time (min)	Flow Rate (ml/min)	Run Time (min)	Flow Rate (ml/min)	Run Time (min)	Flow Rate (ml/min)
-	-	13	82	12	80	14	60	11	857
20	64	-	-	-	-	22	86	-	-
-	-	37	76	38	70	39	86	36	800
-	-	47	72	49	72	48	82	46	857
-	-	57	70	59	56	58	76	56	800
-	-	73	68	75	56	74	76	72	800
-	-	103	62	105	48	104	86	102	800
-	-	123	74	125	46	124	88	122	750
-	-	-	-	128	86	-	-	-	-
145	48	143	76	146	86	144	81	142	857
166	40	162	78	165	96	163	80	161	857
177	40	174	76	176	88	175	90	172	800
208	40	212	76	215	100	217	88	211	800
209	104	-	-	-	-	-	-	-	-
219	78	-	-	-	-	-	-	-	-
230	66	227	76	229	108	228	88	226	800
250	60	247	74	249	84	248	86	246	800
266	60	263	74	265	84	264	88	-	-
309	58	309	86	311	104	308	90	306	857
323	42	317	86	319	112	318	92	316	800
335	52	332	88	334	106	332	90	331	800
349	46	345	80	348	114	347	92	344	800
380	44	379	90	380	114	378	92	378	857
381	80	-	-	382	92	-	-	-	-
396	76	392	90	394	96	393	92	391	857
406	78	403	82	405	94	404	92	401	857
415	80	412	78	414	96	413	92	411	857
427	80	423	86	425	98	424	92	422	800
435	78	435	90	435	100	435	92	435	857

Notes:
(a) Blowdown commenced at 10 minutes, SGTRs at 140, 215, 310 and 390 minutes.
(b) Primary flow adjusted after 209, 219 and 380 minutes; S-1 after 110 and 300 minutes, IKP-4 after 128, 300 and 380 minutes and blowdown after 22 minutes.

161

TABLE 5-19

ANALYTICAL RESULTS, TEST 10 (T-1998)

Run Time (min)	Primary			Model Boiler						SORV Condensate		
				S-1			IKP-4					
	Li (ppb)	K (ppm)	Conductivity (μS/cm)	Li (ppm)	K (ppm)	Conductivity (μS/cm)	Li (ppm)	K (ppm)	Conductivity (μS/cm)	Li (ppb)	K (ppb)	Resistivity (MΩ cm)
-20	-	-	81	-	-	345	-	-	355	-	-	0.240
-10	-	-	81	-	-	340	-	-	355	-	-	0.245
0	0.5	16	81	10	0.250	337	9.5	0.240	351	~0	4.0	0.245
15	-	-	81	10	0.250	339	9.5	0.240	346	~0	~0.2	0.266
30	~0.2	17	80	9	0.250	327	9	0.240	341	~0	~0	0.247
35	-	-	80	9	1	317	9	0.240	337	~0.2	~0	0.053
40	-	-	80	9	3	326	9.5	2	354	0.3	~0.2	0.024
45	-	-	80	9.5	3	318	9	5	350	0.3	~0	0.019
50	-	-	79	8.5	5	318	9	5	341	~0.1	~0	0.017
55	-	-	79	-	-	327	-	-	341	~0.2	~0.1	0.017
60	-	-	78	8.5	8	334	8.5	7.5	349	~0.1	0.3	0.017
65	-	-	78	-	-	327	-	-	352	~0.1	0.4	0.015
68	-	-	77	-	-	329	-	-	349	1.5	3.9	0.023
70	-	-	77	-	-	352	-	-	346	1.5	12.2	0.022
75	0.3	16	76	8.5	12	340	8.5	12	372	2.7	5.9	0.015
80	-	-	76	-	-	357	-	-	373	~0.2	1.2	0.020
85	-	-	75	-	-	328	-	-	372	~0.1	0.6	0.020
90	~0	12	74	7	14	333	8	14	343	~0.2	0.6	0.018
95	-	-	74	-	-	307	-	-	345	~0.2	0.6	0.017
100	-	-	73	-	-	284	-	-	321	11.7	14.9	0.015
105	-	-	73	6.5	16	289	6.5	15	313	~0	7.8	0.019
110	-	-	72	-	-	265	-	-	300	~0	0.4	0.017
115	-	-	72	-	-	262	-	-	278	~0.2	0.5	0.017
120	~0	12	71	5	15.5	245	5	16	277	~0	1.0	0.018
125	-	-	71	-	-	221	-	-	254	~0	~0.2	0.018
129	-	-	71	-	-	225	-	-	235	~0	0.4	0.019
135	-	-	70	4	17	202	4	15	232	~0	~0.2	0.019
140	-	-	70	-	-	183	-	-	210	0.8	1.0	0.019
142	-	-	69	-	-	177	-	-	202	30	90	0.019
144	-	-	69	-	-	189	-	-	195	~0	170	0.020
150	~0	11	69	3	15	167	3	15	192	~0	0.8	0.019
155	-	-	68	-	-	151	-	-	173	1.5	2.9	0.019
160	-	-	68	-	-	141	-	-	157	5.0	20	0.020
161	-	-	68	-	-	147	-	-	155	~0	0.4	0.020
165	-	-	68	2	14	139	2.5	12.5	157	~0	14	0.020
170	-	-	67	-	-	125	-	-	145	~0	~0	0.020
175	-	-	67	-	-	114	-	-	130	4.0	20	0.020

TABLE 5-19 (CONTINUED)

ANALYTICAL RESULTS, TEST 10 (T-1998)

Run Time (min)	Primary			Model Boiler						SORV Condensate		
				S-1			IKP-4					
	Li (ppb)	K (ppm)	Conductivity (µS/cm)	Li (ppm)	K (ppm)	Conductivity (µS/cm)	Li (ppm)	K (ppm)	Conductivity (µS/cm)	Li (ppb)	K (ppb)	Resistivity (MΩ cm)
180	~0	11	67	2	13	151	2	12	127	~0	2.3	0.080
183	-	-	67	-	-	122	-	-	147	~0	~0	0.129
185	-	-	67	-	-	146	-	-	169	~0	~0	0.190
187	-	-	67	-	-	117	-	-	200	~0	~0	0.362
190	~0	11	67	1	7	20	3	22	274	~0	~0	0.591
192	-	-	67	-	-	13	-	-	400	~0	~0	0.548
193	-	-	67	-	-	12	-	-	464	0.3	3.2	0.538
205	-	-	67	0.130	0.450	9	1	5	34	-	-	0.886
220	~0	11	67	0.060	0.140	9	5	44	1070	-	-	0.337
230	-	-	67	-	-	9	-	-	1120	-	-	0.340

Notes:
(a) SGTR extended from 30 to 190 minutes. Boildown from 174 to 191 minutes.
(b) Conductivity and resistivity data taken from the computer output for the period 0-220 minutes and from the recorder trace at other times.
(c) All SORV condensate analyses, except where noted below, and all lithium analyses on primary samples were carried out using the 0-20 ppb ranges. Precision ±0.1 to 0.3 ppb.
(d) All other analyses, except where noted below, were carried out at a 1:100 dilution using the 0-1000 ppb ranges. Precision ±0.2 to 1.2 ppm.
(e) Potassium analyses on the SORV condensate samples at 142 and 144 minutes, S-1 samples at 0, 15, 30, 205 and 220 minutes and IKP-4 samples at 0, 15, 30 and 35 minutes were analysed undiluted on the 0-1000 ppb range.
(f) Lithium analyses on the SORV condensate sample at 142 minutes and the S-1 samples at 205 and 220 minutes were analysed undiluted using the 0-1000 ppb range.
(g) The void space of the model boiler contained 2 ppm lithium and 5 ppm potassium when analysed after 170 and 180 minutes.
(h) Pre-test the make-up tank contained ~13 mg kg^{-1} potassium and 10 ppm hydrazine and the surge tank ~3 ppm oxygen and 6 ppm hydrazine. The primary loop contained <5 ppb oxygen and 0.03 ppm hydrazine.

TABLE 5-20

SAMPLE LINE FLOW RATES, TEST 10 (T-1998)

Primary		Model Boiler				SORV Condensate	
		S-1		IKP-4			
Run Time (min)	Flow Rate (ml/min)	Run Time (min)	Flow Rate (ml/min)	Run Time (min)	Flow Rate (ml/min)	Run Time (min)	Flow Rate (ml/min)
-28	86	-30	78	-30	80	-30	632
6	84	3	78	5	78	2	571
21	84	18	80	26	78	17	600
40	66	38	80	39	80	36	600
52	68	48	80	49	80	47	632
64	68	63	82	65	80	62	600
82	66	80	70	81	82	78	706
108	68	106	66	107	82	-	-
124	68	120	68	122	82	119	261
-	-	-	-	-	-	128	600
154	66	152	64	153	80	151	286
171	64	171	62	170	80	170	133
184	64	182	30	183	64	180	750
-	-	-	-	-	-	186	750
199	66	196	46	198	60	-	-
212	64	210	50	211	62	-	-
220	64	220	52			221	214

Note: SORV condensate flow stopped after a number of the pressure relief cycles for the following periods, 72-74, 91-92, 103-105, 117-118 and 129-129.5 minutes. On each occasion the flow rate recovered over several minutes. After the SORV flow was stopped at 191 minutes a slow erratic SORV condensate flow was maintained for the rest of the test.

TABLE 5-21

ANALYTICAL RESULTS, TEST 11 (T-2003)

Run Time (min)	Primary			Model Boiler						SOHV Condensate		
				S-1			IKP-4					
	Li (ppb)	K (ppm)	Conductivity (μS/cm)	Li (ppm)	K (ppm)	Conductivity (μS/cm)	Li (ppm)	K (ppm)	Conductivity (μS/cm)	Li (ppb)	K (ppb)	Resistivity (MΩ cm)
-20	-	-	76	-	-	370	-	-	390	-	-	0.940
-10	-	-	76	-	-	365	-	-	385	-	-	-
0	~0.2	8	76	10	0.150	366	11	0.160	381	~0	~0	-
15	~0.2	8	76	11	0.150	362	11	0.160	377	~0	~0	-
25	-	-	76	-	-	356	-	-	372	~0	~0	-
30	~0.2	8	76	11	0.160	355	11	0.160	371	~0.1	~0	-
35	-	-	76	11	0.760	346	11	0.160	370	-	-	-
40	-	-	75	11	3	341	11	0.730	368	-	-	-
43.5	-	-	-	-	-	-	-	-	-	2.6	12.2	-
44	-	-	-	-	-	-	-	-	-	2.0	3.8	-
44.5	-	-	-	-	-	-	-	-	-	1.0	5.4	-
45	-	-	75	10	3	332	10.5	3	360	0.8	2.4	-
45.5	-	-	-	-	-	-	-	-	-	0.8	2.8	-
50	-	-	74	10	6	345	11	4	372	-	-	-
53	-	-	-	-	-	-	-	-	-	0.6	1.4	-
59.5	-	-	-	-	-	-	-	-	-	16	7.6	-
60	~0.2	8	72	9	6.5	295	10	5	328	10.4	6.0	-
60.5	-	-	-	-	-	-	-	-	-	3.2	3.8	-
61	-	-	-	-	-	-	-	-	-	3.2	3.0	-
61.5	-	-	-	-	-	-	-	-	-	3.2	3.0	-
67	-	-	-	-	-	-	-	-	-	2.2	1.2	-
70	~0.2	9	72	8	6.5	278	8.5	7	307	-	-	-
77.5	-	-	-	-	-	-	-	-	-	13.6	12.4	-
78	-	-	-	-	-	-	-	-	-	0.6	5.6	-
78.5	-	-	-	-	-	-	-	-	-	0.4	6.4	-
79	-	-	-	-	-	-	-	-	-	0.3	~0	-
79.5	-	-	-	-	-	-	-	-	-	0.4	~0.2	-
80	-	-	71	6.5	7	251	7	7	267	-	-	-
85	-	-	-	-	-	-	-	-	-	0.4	~0	-
90	~0.2	8	78	6	9	223	6	8	249	-	-	-
98.5	-	-	-	-	-	-	-	-	-	14.4	16.6	-
99.5	-	-	-	-	-	-	-	-	-	~0.2	3.2	-
99	-	-	-	-	-	-	-	-	-	~0.2	5.2	-
100	-	-	82	5	9	194	5	9	216	~0.2	3.2	-
100.5	-	-	-	-	-	-	-	-	-	~0.2	1.6	-
110	-	-	82	5	9.5	178	5	9	200	-	-	-
120	~0.2	8	80	4	9.5	151	4	9	168	-	-	-
125	-	-	-	-	-	-	-	-	-	9.6	11.6	-
130	-	-	78	3	9	131	4	9	146	-	-	-

TABLE 5-21 (CONTINUED)

ANALYTICAL RESULTS, TEST 11 (T-2003)

Run Time (min)	Primary			Model Boiler						SOHV Condensate		
				S-1			IKF-4					
	Li (ppb)	K (ppm)	Conductivity (µS/cm)	Li (ppm)	K (ppm)	Conductivity (µS/cm)	Li (ppm)	K (ppm)	Conductivity (µS/cm)	Li (ppb)	K (ppb)	Resistivity (MΩ cm)
130.25	-	-	-	-	-	-	-	-	-	80	130	-
130.5	-	-	-	-	-	-	-	-	-	14.4	20	-
130.75	-	-	-	-	-	-	-	-	-	3.6	6.2	-
131	-	-	-	-	-	-	-	-	-	0.3	~0	-
131.25	-	-	-	-	-	-	-	-	-	~0.2	2.4	-
131.5	-	-	-	-	-	-	-	-	-	0.4	~0	-
132	-	-	-	-	-	-	-	-	-	~0.2	~0	-
132.5	-	-	-	-	-	-	-	-	-	0.3	1.0	-
140	-	-	77	3	9	125	3	9	140	-	-	-
149	-	-	-	-	-	-	-	-	-	6.0	19.6	-
150	~0.2	9	77	2.5	9	108	3	9	122	-	-	-
160	-	-	75	2	9	98	3	9	108	-	-	-
160.25	-	-	-	-	-	-	-	-	-	130	510	-
160.5	-	-	-	-	-	-	-	-	-	15	50	-
160.75	-	-	-	-	-	-	-	-	-	1.2	5.6	-
161	-	-	-	-	-	-	-	-	-	~0.2	2.4	-
161.25	-	-	-	-	-	-	-	-	-	~0.2	1.0	-
161.5	-	-	-	-	-	-	-	-	-	~0	0.5	-
162	-	-	-	-	-	-	-	-	-	~0	~0.2	-
162.5	-	-	-	-	-	-	-	-	-	~0	~0	-
163	-	-	-	-	-	-	-	-	-	~0	~0	-
163.5	-	-	-	-	-	-	-	-	-	~0.2	~0	-
164	-	-	-	-	-	-	-	-	-	~0.2	~0.2	-
165	-	-	74	-	-	113	-	-	111	~0	0.6	-
166	-	-	-	-	-	-	-	-	-	~0	~0.2	-
167	-	-	-	-	-	-	-	-	-	~0.2	~0.2	-
168	-	-	-	-	-	-	-	-	-	~0.2	1.2	-
169	-	-	-	-	-	-	-	-	-	~0	~0	-
170	-	-	73	2	13	147	2	11	138	~0.2	~0.2	-
171	-	-	-	-	-	-	-	-	-	~0.2	~0.2	-
172	-	-	-	-	-	-	-	-	-	~0.2	~0	-
173	-	-	-	-	-	-	-	-	-	~0	~0	-
174	-	-	-	-	-	-	-	-	-	~0.2	~0.2	-
175	-	-	73	-	-	122	-	-	174	~0.2	~0.2	-
176	-	-	-	-	-	-	-	-	-	~0.2	~0	-
177	-	-	-	-	-	-	-	-	-	~0.2	~0	-
178	-	-	-	-	-	-	-	-	-	~0	~0	-
179	-	-	-	-	-	-	-	-	-	~0	~0.2	-

TABLE 5-21 (CONTINUED)

ANALYTICAL RESULTS, TEST 11 (T-2003)

Run Time (min)	Primary			Model Boiler						SORV Condensate		
				S-1			IKP-4					
	Li (ppb)	K (ppm)	Conductivity (μS/cm)	Li (ppm)	K (ppm)	Conductivity (μS/cm)	Li (ppm)	K (ppm)	Conductivity (μS/cm)	Li (ppb)	K (ppb)	Resistivity (MΩ cm)
180	~0.2	9	72	2	16	168	2	22	235	~0	~0	-
181	-	-	-	-	-	-	-	-	-	~0.2	~0	-
182	-	-	-	-	-	-	-	-	-	~0	~0	-
183	-	-	-	-	-	-	-	-	-	~0.2	~0	-
184	-	-	-	-	-	-	-	-	-	~0	~0	-
185	-	-	72	-	-	34	-	-	372	~0	~0	-
186	-	-	-	-	-	-	-	-	-	~0	~0	-
187	-	-	-	-	-	-	-	-	-	~0	~0	-
188	-	-	-	-	-	-	-	-	-	~0	~0	-
189	-	-	-	-	-	-	-	-	-	~0	1.2	-
190	-	-	71	0.030	0.090	29	2	59	737	~0	1.4	-
191	-	-	-	-	-	-	-	-	-	~0	2.6	-
192	-	-	-	-	-	-	-	-	-	~0.2	5.0	-
193	-	-	-	-	-	-	-	-	-	0.6	20	-
194	-	-	-	-	-	-	-	-	-	1.4	30	-
195	-	-	71	-	-	41	-	-	1030	1.0	18.4	-
196	-	-	-	-	-	-	-	-	-	80	670	-
196.5	-	-	-	-	-	-	-	-	-	0.8	6	-
197	-	-	-	-	-	-	-	-	-	0.5	2.4	-
200	-	-	70	0.030	0.215	27	2	22	74	-	-	-
215	~0.2	9	70	0.020	0.060	7	18	225	215	-	-	-
230	~0.2	9	70	0.015	0.040	5	15	194	1900	-	-	-

Notes:

(a) SGTR extended from 30 to 200 minutes, boildown from 160 to 190 minutes. The pressure relief cycles occurred at 43, 59, 77, 98, 130 and 160 minutes.

(b) Conductivity and resistivity data taken from the computer output for the period 0-220 minutes and from the recorder trace at other times.

(c) All SORV condensate analyses, except as noted below, and all lithium analyses on primary samples were carried out using the 0-20 ppb ranges. Precision ±0.1 to 0.3 ppb.

(d) All other analyses, except as noted below, carried out at a dilution of 1:100 using the 0-1000 ppb ranges. Precision ±0.2 to 1.2 ppm.

(e) Lithium analyses on SORV condensate samples after 130.25, 160.25 and 196 minutes and potassium analyses on SORV condensate samples after 130.25, 160.25, 160.5, 193, 194 and 196 minutes analysed undiluted using the 0-1000 ppb range. Precision ±2 to 12 ppb.

(f) S-1 samples from 190 to 230 minutes, and potassium analyses on S-1 samples from 0 to 35 minutes and IKP-4 samples from 0 to 40 minutes were analysed undiluted using the 0-1000 ppb range. The IKP-4 sample after 215 minutes was analysed at a dilution of 1:500 and that after 230 minutes at 1:200 (both for potassium only).

(g) The make-up tank pre-test contained 10 ppm potassium, 3 ppm oxygen and 14 ppm hydrazine. The surge tank contained 4 ppm oxygen and 16 ppm hydrazine. The primary loop contained <5 ppb oxygen and ~1 ppm hydrazine and the model boiler <10 ppb, oxygen 0.01 ppm hydrazine and <2 ppm ammonia.

TABLE 5-22

SAMPLE LINE FLOW RATES, TEST 11 (T-2003)

Primary		Model Boiler				SORV Condensate	
		S-1		IKP-4			
Run Time (min)	Flow Rate (ml/min)	Run Time (min)	Flow Rate (ml/min)	Run Time (min)	Flow Rate (ml/min)	Run Time (min)	Flow Rate (ml/min)
-19	76	-23	78	-21	86	0	0
4	74	2	78	3	82	-	-
16	74	18	76	17	82	-	-
31	72	32	82	32	82	-	-
46	76	48	80	47	100	-	-
64	72	62	72	63	100	-	-
76	72	78	70	77	106	-	-
93	70	91	72	92	106	-	-
105	70	108	70	106	104	-	-
123	68	121	72	122	108	-	-
136	68	135	64	137	102	-	-
-	-	138	86	-	-	-	-
153	68	151	88	152	102	-	-
167	66	164	70	165	86	-	-
185	70	183	52	184	82	-	-
196	64	194	56	195	82	-	-
221	66	218	56	220	72	-	-
235	66	233	58	234	74	-	-

Notes: (a) SORV condensate line disconnected.
(b) S-1 flow adjusted after 137 minutes.

TABLE 5-23

ANALYTICAL RESULTS, TEST 12 (T-2001)

Run Time (min)	Primary			Model Boiler						SORV Condensate		
				S-1			IKP-4					
	Li (ppb)	K (ppm)	Conductivity (µS/cm)	Li (ppm)	K (ppm)	Conductivity (µS/cm)	Li (ppm)	K (ppm)	Conductivity (µS/cm)	Li (ppb)	K (ppb)	Resistivity (MΩ cm)
-20	-	-	68	-	-	355	-	-	320	-	-	0.500
-10	-	-	68	-	-	350	-	-	318	-	-	0.505
0	0.5	8	68	11	0.050	345	10	0.060	318	~0.2	~0	0.470
15	-	-	68	11	0.065	337	10	0.060	312	~0.2	5.8	0.474
30	0.5	8	68	11	0.060	328	10	0.060	306	~0.2	~0	0.499
35	-	-	68	11	0.600	327	10	0.060	302	~0.2	~0.2	0.100
40	-	-	67	11	3	348	10	2	317	0.3	0.3	0.090
45	-	-	67	9	4	236	10	4	334	0.8	6.0	0.067
50	-	-	66	-	-	152	-	-	500	~0	0.6	0.020
55	-	-	65	-	-	192	-	-	410	~0	0.4	0.015
60	~0.2	8	64	7	6	235	9	7	289	0.3	0.8	0.011
65	-	-	64	-	-	230	-	-	265	~0.2	9.6	0.020
70	-	-	63	-	-	250	-	-	260	~0.1	1.0	0.022
75	-	-	62	6	10	257	7	10	273	~0	0.8	0.020
80	-	-	62	-	-	271	-	-	284	~0	0.7	0.028
85	-	-	61	-	-	311	-	-	302	~0	0.5	0.036
90	0.8	8	58	7	16	313	7	16	328	0.3	~0.2	0.035
95	-	-	58	-	-	319	-	-	333	~0.2	~0	0.039
100	-	-	57	-	-	328	-	-	343	~0	~0	0.040
105	-	-	57	7	19	326	7	19	348	~0.2	~0.2	0.037
115	-	-	57	-	-	326	-	-	348	~0	~0	0.035
120	0.4	8	56	7	21	333	7	20	352	-	-	0.034
125	-	-	56	-	-	329	-	-	360	~0.2	6.0	0.033
135	~0.2	8	56	7	23	334	7	23	361	~0.2	~0	0.033
145	-	-	55	-	-	348	-	-	367	~0	~0.2	0.033
150	0.4	8	55	-	-	351	-	-	372	-	-	0.033
155	-	-	55	7	28	352	7	29	376	~0	~0	0.033
165	-	-	55	-	-	356	-	-	381	~0	~0	0.034
175	-	-	54	-	-	354	-	-	382	~0	~0	0.034
180	~0.2	8	54	-	-	354	-	-	382	-	-	0.034
185	-	-	54	-	-	354	-	-	382	~0	~0.2	0.034
195	-	-	53	6	30	366	7	30	387	~0	0.8	0.034
205	-	-	53	-	-	371	-	-	395	~0	~0	0.034
210	~0.2	8	53	-	-	372	-	-	396	-	-	0.034
215	-	-	53	-	-	372	-	-	399	~0	0.8	0.035
225	-	-	52	6	33	371	7	32	401	~0.2	0.6	0.034
235	-	-	52	-	-	368	-	-	399	~0	0.4	0.031
240	~0.2	8	52	-	-	368	-	-	398	-	-	0.031
245	-	-	52	-	-	366	-	-	396	~0	0.4	0.031
255	~0.2	8	52	6	32	356	6	33	395	~0	0.6	0.030

169

TABLE 5-23 (CONTINUED)

ANALYTICAL RESULTS, TEST 12 (T-2001)

Run Time (min)	Primary			Model Boiler						SORV Condensate		
				S-1			IKP-4					
	Li (ppb)	K (ppm)	Conductivity (µS/cm)	Li (ppm)	K (ppm)	Conductivity (µS/cm)	Li (ppm)	K (ppm)	Conductivity (µS/cm)	Li (ppb)	K (ppb)	Resistivity (MΩ cm)
265	-	-	52	-	-	346	-	-	392	~0	0.6	0.029
275	-	-	52	-	-	335	-	-	382	~0	0.6	0.028
285	~0.2	8	51	5	31	323	6	33	365	0.4	~0	0.028
300	-	-	51	-	-	306	-	-	341	~0.2	~0	0.026
315	~0.2	8	51	5	29	288	5	30	323	~0.2	~0	0.024
330	-	-	50	-	-	354	-	-	305	0.3	1.0	0.029
345	0.3	8	50	4	27	258	4	29	283	1.0	7.2	0.026
360	-	-	50	-	-	246	-	-	265	~0.2	~0.2	0.019
375	0.3	8	49	4	26	245	4	26	244	-	-	0.074
390	~0.2	8	49	4	25	233	3	24	244	-	-	0.070

Notes:
(a) SGTR extended from 30 to 390 minutes.
(b) Conductivity and resistivity data taken from the computer output for the period 0-390 minutes and from the recorder trace at other times.
(c) All SORV condensate analyses and lithium analyses on primary samples carried out using the 0-20 ppb ranges. Precision ±0.1 to 0.3 ppb.
(d) All other samples, except where noted below, were analysed at a dilution of 1:100 using the 0-1000 ppb ranges. Precision ±0.2 to 1.2 ppm.
(e) S-1 and IKP-4 samples taken after 0,15,30 and 35 minutes were analysed for potassium using the 0-1000 ppb range without dilution.
(f) Pre-test the make-up tank contained 9.5 ppm potassium, 3 ppm oxygen and 10 ppm hydrazine and the surge tank 3 ppm oxygen and ~4 ppm hydrazine. The primary loop contained <5 ppb oxygen and 1.5 ppm hydrazine.

TABLE 5-24

SAMPLE LINE FLOW RATES, TEST 12 (T-2001)

Primary		Model Boiler				SORV Condensate	
		S-1		IKP-4			
Run Time (min)	Flow Rate (ml/min)	Run Time (min)	Flow Rate (ml/min)	Run Time (min)	Flow Rate (ml/min)	Run Time (min)	Flow Rate (ml/min)
2	70	0	82	1	92	0	667
29	72	27	76	30	90	25	667
43	50	42	84	42	98	41	667
56	70	54	70	54	78	-	-
78	32	73	40	79	68	73	731
87	84	80	84	83	82	88	682
99	74	97	72	98	76	96	667
112	66	109	60	110	66	108	667
124	64	123	50	125	60	123	667
137	62	138	40	136	56	135	667
141	92	140	82	140	80	-	-
151	86	150	80	151	76	150	667
178	74	176	66	177	66	175	667
191	72	189	54	190	62	188	667
211	64	208	50	210	56	208	667
229	62	227	44	228	52	227	667
243	58	241	40	242	50	240	667
259	56	258	34	259	42	257	600
-	-	265	88	-	-	-	-
289	54	288	68	288	48	287	667
303	44	301	64	302	44	300	571
322	44	321	56	322	40	320	632
330	42	329	50	329	38	328	667
348	40	347	46	348	48	347	667
368	60	364	44	367	44	363	171
375	120	377	44	376	68	-	-
390	114	391	40	390	66	-	-

Notes: (a) SORV flow halted at 363 minutes.
(b) Primary flow rates adjusted after 86, 140 and 374 minutes; S-1 rates adjusted after 79, 139 and 264 measures and IKP-4 rates after 82, 139 and 375 minutes.

TABLE 5-25

ANALYTICAL RESULTS, TEST 13 (T-2069)

Run Time (min)	Model Boiler		SORV Condensate	
	Li (ppm)	Conductivity (μS/cm)	Li (ppb)	Resistivity (MΩ cm)
-40	-	50(e)	-	-
-30	-	1085	-	0.130
-20	-	980	-	0.530
-10	-	880	-	0.380
0	26	804	0.6	0.317
5	-	769	-	0.304
10	24	723	0.4	0.332
15	26	693	0.4	0.345
20	-	680	0.4	0.365
25	21	633	0.7	0.334
30	21	571	1.6	0.321
35	18	508	2.2	0.307
40	15	450	1.8	0.294
45	14	401	1.8	0.284
50	14	368	1.4	0.278
55	-	349	-	0.278
60	-	330	-	0.271

Notes:
(a) Conductivity and resistivity data taken from the computer output, except for the period before the test commenced when it was estimated from the recorder trace.
(b) All S-1 samples analysed at 1:100 dilution using the 0-1000 ppb range. Precision ±0.2 to 1.2 ppm.
(c) All SORV condensate samples analysed using the 0-20 ppb range. Precision ±0.1 to 0.3 ppb.
(d) Pre-test the surge tank contained 2 ppm oxygen and ~0 ppm hydrazine.
(e) Pre-dose value.

TABLE 5-26

SAMPLE LINE FLOW RATES, TEST 13 (T-2069)

Model Boiler				SORV Condensate	
S-1		IKP-4			
Run Time (min)	Flow Rate (ml/min)	Run Time (min)	Flow Rate (ml/min)	Run Time (min)	Flow Rate (ml/min)
4	156	6	142	4	732
11	154	11	144	10	732
18	154	-	-	22	732
26	152	-	-	-	-
31	158	-	-	31	750
37	158	-	-	36	750
46	154	-	-	46	750

Note: IKP-4 sample flow halted after ~15 minutes.

TABLE 5-27

ANALYTICAL RESULTS, TEST 14 (T-2067)

Run Time (min)	Primary			Model Boiler						SOHV Condensate		
				S-1			IKP-4					
	Li (ppb)	K (ppm)	Conductivity (µS/cm)	Li (ppm)	K (ppm)	Conductivity (µS/cm)	Li (ppm)	K (ppm)	Conductivity (µS/cm)	Li (ppb)	K (ppb)	Resistivity (MΩ cm)
-20	-	-	201	-	-	1310	-	-	1380	-	-	1.370
-10	-	-	201	-	-	1265	-	-	1350	-	-	1.510
0	3.4	50	201	37	0.090	1251	36	0.080	1306	~0	~0	1.438
15	-	-	201	36	0.080	1231	36	0.090	1290	~0	4.0	1.409
20	-	-	201	36	1	1239	36	0.100	1288	0.5	1.2	0.058
25	-	-	201	36	5	1242	37	4	1323	~0.2	0.6	0.029
30	3.4	50	200	35	8	1244	36	7	1312	~0.2	0.4	0.024
45	-	-	202	35	23	1323	36	21	1386	~0.2	~0	0.020
60	3.0	50	206	35	50	1389	36	35	1452	~0.2	0.3	0.022
75	-	-	208	35	55	1463	36	50	1527	~0	0.4	0.022
80	-	-	210	-	-	1489	-	-	1551	~0	~0	0.039
82.5	-	-	210	37	61	1484	36	58	1545	-	-	0.061
85	-	-	210	-	-	1294	-	-	1541	~0	~0	0.096
90	2.8	50	211	24	40	1021	36	56	1569	~0	~0	0.271
95	-	-	211	-	-	999	-	-	1577	~0	~0	0.686
97.5	-	-	211	4	8	170	33	53	1599	-	-	1.098
100	-	-	211	-	-	21	-	-	1763	~0	~0	1.574
105	-	-	212	0.200	1.5	10	43	70	1986	~0	~0	1.786
110	-	-	212	-	-	6	-	-	2034	~0.2	~0	1.672
112.5	-	-	212	0.100	1	5	45	72	2047	-	-	1.568
115	-	-	212	-	-	4	-	-	2047	0.5	~0	1.466
120	2.4	52	212	0.060	0.120	3	46	75	2059	~0.2	~0	1.286
123	-	-	212	-	-	26	-	-	2047	1.0	50	0.037
125	-	-	212	-	-	35	-	-	2010	0.6	60	0.028
127.5	-	-	212	0.060	0.100	37	43	77	2121	-	-	0.025
130	-	-	211	-	-	39	-	-	2230	0.4	20	0.024
135	-	-	212	0.040	0.050	38	46	114	2316	0.4	0.8	0.024
150	2.0	52	216	0.020	0.030	43	43	230	2596	~0	0.4	0.022
165	-	-	219	0.0060	0.020	43	44	230	3232	~0.2	~0	0.022
180	2.0	52	223	0.0044	0.015	46	43	280	3451	~0.2	1.6	0.020
195	-	-	227	0.0024	0.015	3	45	315	4062	~0	~0	0.567
210	1.6	50	228	0.0018	0.010	2	42	300	3806	~0	~0	0.596

Notes: (a) SGTRs extended from 15 to 75 and 120 to 180 minutes, blowdown from 80 to 103 minutes.

(b) Conductivity and resistivity data taken from the computer output for the period 0 to 195 minutes and from the recorder trace at other times.

(c) All SOHV analyses, except where noted below, and all lithium analyses on primary samples were carried out using the 0-20 ppb ranges. Precision ±0.1 to 0.3 ppb. Lithium analyses on S-1 samples from 165 to 210 minutes were also carried out using this range.

(d) All other analyses were carried out using the 0-1000 ppb ranges, either undiluted (potassium analysis on SOHV condensate samples from 123 to 130 minutes, lithium analyses on S-1 samples from 105 to 210 minutes, potassium analyses on S-1 samples from 0 to 15 and 120 to 210 minutes, IKP-4 samples from 0 to 15 minutes), or diluted 1:100, 1:200 (potassium analyses on the IKP-4 sample after 150 minutes) or 1:500 (potassium on IKP-4 samples from 165 to 210 minutes).

(e) Pre-test the make-up tank contained 71 ppm potassium and 16 ppm hydrazine, the surge tank 2 ppm oxygen and ~5 ppm hydrazine and the primary loop <5 ppb oxygen and 0.01 ppm hydrazine.

TABLE 5-28

SAMPLE LINE FLOW RATES, TEST 14 (T-2067)

Primary		Model Boiler				SORV Condensate	
		S-1		IKP-4			
Run Time (min)	Flow Rate (ml/min)	Run Time (min)	Flow Rate (ml/min)	Run Time (min)	Flow Rate (ml/min)	Run Time (min)	Flow Rate (ml/min)
6	58	4	90	5	91	3	667
22	56	21	88	22	94	21	682
37	58	36	88	36	96	35	667
53	56	52	88	52	94	51	667
77	57	76	88	76	92	75	667
93	53	91	76	92	94	91	682
112	54	109	78	111	93	109	682
122	53	121	79	122	94	120	625
137	51	136	80	136	96	135	667
153	50	151	79	152	88	150	682
178	50	176	76	177	82	176	652
183	50	181	74	182	78	180	652
198	50	196	72	197	78	195	667
208	49	207	74	208	79	207	682

TABLE 5-29

ANALYTICAL RESULTS, TEST 15 (T-2050 to T-2054)

Run Time (min)	Primary			Model Boiler						SORV Condensate		
				S-1			IKP-4					
	Li (ppb)	K (ppm)	Conductivity (μS/cm)	Li (ppm)	K (ppm)	Conductivity (μS/cm)	Li (ppm)	K (ppm)	Conductivity (μS/cm)	Li (ppb)	K (ppb)	Resistivity (MΩ cm)
-30	-	-	290	-	-	275	-	-	270	-	-	-
-20	-	-	300	-	-	270	-	-	270	-	-	0.097
-10	-	-	300	-	-	270	-	-	270	-	-	1.330
0	-	-	301	-	-	268	-	-	269	~0	~0	1.349
1	-	-	301	8	0.090	268	8	0.090	269	-	-	1.349
5	-	-	299	8	0.090	264	8	0.090	268	~0	~0.2	1.354
10	-	-	299	7.5	0.100	262	8	0.090	267	~0	~0.2	1.353
15	-	-	299	6	0.080	214	8	0.090	263	~0	~0.2	1.369
20	-	-	299	5	0.075	180	8	0.090	262	~0	~0	1.339
25	-	-	300	5	0.050	160	8	0.090	254	~0	1.4	1.303
30	-	-	299	4	0.050	135	7	0.090	235	~0	~0	1.314
35	-	-	295	3	0.040	108	6	0.080	210	~0	~0	1.323
40	-	-	295	2	0.040	90	5.5	0.060	177	~0	~0	1.364
45	-	-	294	2	0.030	77	5	0.050	148	~0	~0	1.436
50	-	-	295	1.000	0.020	35	4	0.040	127	~0	~0.2	1.729
52.5	-	-	294	-	-	10	-	-	113	3.0	~0.2	1.300
55	-	-	294	0.070	0.0014	5	3	0.030	94	4.6	~0	0.936
57.5	-	-	295	-	-	4	-	-	89	0.5	~0	0.900
60	-	-	295	0.030	0.0008	3	3	0.040	83	0.8	~0	0.807
65	-	-	295	0.0164	~0	2	2.5	0.040	74	1.0	~0	0.861
70	-	-	293	0.0064	~0.0002	2	2	0.040	65	0.4	~0	0.972
75	1.8	53	295	0.0078	0.0005	1	2	0.025	45	0.4	~0	1.248
90	-	-	295	-	-	1	-	-	22	~0	~0	1.320
105	2.6	53	290	0.0074	0.0004	1	0.400	0.0108	16	0.6	~0	1.330
120	-	-	290	-	-	1	-	-	10	1.0	~0	1.320
135	3.0	53	290	0.0052	0.0056	1	0.360	0.0116	12	0.4	~0	1.340
150	3.0	54	289	0.0040	0.0008	1	0.140	0.0054	8	0.8	~0	1.393
152.5	-	-	291	-	-	10	-	-	7	1.8	0.8	0.060
155	-	-	293	0.0050	0.030	54	0.100	0.0054	6	25	8.2	0.019
160	-	-	289	0.0060	0.050	57	0.260	2.0	25	14.0	60	0.018
165	-	-	294	-	-	57	-	-	57	6.0	100	0.018
170	-	-	293	0.030	0.400	56	0.420	8.0	74	3.6	110	0.019
175	-	-	288	-	-	54	-	-	83	2.6	120	0.019
180	3.4	55	284	0.030	0.600	53	0.370	12.0	100	1.6	120	0.020
185	-	-	279	-	-	10	-	-	113	~0.2	40	0.123
190	-	-	278	0.0042	0.180	2	0.320	12.0	104	~0.2	100	0.797
200	-	-	278	0.0032	0.230	2	0.420	6.0	64	0.3	130	0.978
205	-	-	277	-	-	2	-	-	56	0.6	100	0.913
210	3.6	55	278	0.0036	0.260	2	0.550	7.0	81	1.2	600	0.285
215	-	-	277	-	-	2	-	-	119	1.8	460	0.615
225	-	-	275	0.0038	0.350	2	0.950	57	405	2.5	520	0.600
240	3.6	55	274	0.0034	0.300	1	0.430	26	400	2.5	470	0.595
255	-	-	273	0.0030	0.250	1	0.380	27	213	1.8	370	0.622
260	-	-	272	0.0028	0.200	1	0.300	19	156	2.0	400	0.600
262	-	-	273	-	-	23	-	-	136	4.4	1000	0.036
265	-	-	273	0.0028	0.110	45	0.270	16	181	7.0	640	0.022
270	3.8	55	273	0.0028	7	62	0.850	190	1617	4.6	220	0.021
275	-	-	272	-	-	51	-	-	2474	2.6	150	0.021
280	-	-	269	0.020	0.700	48	2	330	2938	1.8	140	0.021

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176

TABLE 5-29 (CONTINUED)

ANALYTICAL RESULTS, TEST 15 (T-2050 to T-2054)

Run Time (min)	Primary			Model Boiler						SORV Condensate		
				S-1			IKP-4					
	Li (ppb)	K (ppm)	Conductivity (µS/cm)	Li (ppm)	K (ppm)	Conductivity (µS/cm)	Li (ppm)	K (ppm)	Conductivity (µS/cm)	Li (ppb)	K (ppb)	Resistivity (MΩ cm)
290	-	-	267	0.020	0.450	45	2	400	3842	1.0	120	0.022
300	4.2	54	265	0.0062	0.570	3	2	400	3647	0.6	470	0.530
310	-	-	260	0.0044	0.540	3	2	365	3280	0.6	610	0.333
315	-	-	263	-	-	3	-	-	3134	0.8	690	0.294
320	-	-	263	0.0032	0.120	1	1.5	290	2487	1.6	690	0.367
323	-	-	262	-	-	94	-	-	1448	1.7	350	0.841
325	-	-	262	-	-	500	-	-	1600	1.4	200	1.000
330	4.2	55	262	0.430	114	900	0.720	190	1750	1.0	70	1.400
345	-	-	262	0.330	100	900	0.720	200	1700	0.3	30	1.830
360	4.2	55	262	0.350	112	842	0.650	200	1644	0.4	20	1.864
365	-	-	261	0.350	104	759	0.630	200	1595	0.3	15	1.864
367	-	-	261	-	-	865	-	-	1619	0.3	25	0.043
370	-	-	262	0.320	108	688	0.640	200	1681	0.3	20	0.024
375	-	-	260	-	-	624	-	-	2047	~0.2	12.4	0.023
380	-	-	261	0.370	154	1058	0.700	283	2242	~0.2	8.6	0.024
390	4.2	55	257	0.350	180	1216	0.700	335	2633	~0.2	9.4	0.025
400	-	-	258	0.290	166	1216	0.660	360	2877	~0	14.4	0.189
410	-	-	258	0.260	175	1216	0.520	325	2621	~0.2	25	1.832
420	4.4	55	257	0.350	185	1387	0.520	320	2548	~0.2	12.0	1.303
435	-	-	257	0.320	150	1070	0.430	205	1570	~0	4.0	1.290
445	-	-	258	0.325	150	1045	0.450	205	1558	~0	2.6	1.303
450	4.4	55	258	0.330	145	1021	0.460	200	1522	~0	2.0	1.320
452.5	-	-	258	-	-	1021	-	-	1522	~0	4.4	0.040
455	-	-	258	0.320	145	1009	0.460	200	1510	~0.2	6.0	0.029
460	-	-	256	0.340	160	1119	0.460	205	1583	~0.2	3.6	0.027
465	-	-	258	-	-	1180	-	-	1705	~0	3.6	0.026
470	-	-	260	0.350	180	1277	0.470	240	1778	~0	3.6	0.028
480	4.6	53	260	0.340	205	1448	0.470	265	1986	~0	4.4	0.029
490	-	-	260	0.350	210	1497	0.470	275	2108	~0	3.0	0.928
500	-	-	262	0.340	210	1473	0.460	275	2096	-	-	1.284
510	-	-	262	-	-	1470	-	-	2000	-	-	1.100

Notes:
(a) SGTRs extended from 151 to 181, 260 to 290, 365 to 395 and 450 to 480 minutes, blowdown from 10 to 65 minutes.
(b) Conductivity and resistivity data taken from the computer outputs for the periods 0 to 75, 146 to 216, 255 to 324, 360 to 425 and 445 to 501 minutes and from the recorder trace at other times.
(c) All SORV condensate analyses, except as noted below, lithium analyses on all primary samples and on S-1 samples from 65 to 160, 190 to 270 and 300 to 320 minutes anad potassium analyses on S-1 samples from 55 to 150 minutes were carried out using the 0-20 ppb ranges. Precision ±0.1 to 0.3 ppb. The 0-1000 ppb ranges were used for the SORV condensate samples taken after 155 minutes (lithium) and 160 to 370 and 410 minutes (potassium).
(d) All other analyses were carried out using the 0-1000 ppb ranges, either undiluted or diluted 1:100 (S-1 samples after 1 to 45 minutes (lithium), IKP-4 samples after 1 to 95 and 280 to 320 minutes (lithium) and 160 to 265 minutes (potassium) and potassium analyses on primary samples), 1:200 (potassium analyses on S-1 samples, 330 to 400 minutes and IKP-4 samples, 270 and 345 to 380 minutes) or 1:500 (potassium analyses on S-1 samples, 410 to 500 minutes) and IKP-4 samples, 280 to 330 and 380 to 500 minutes).
(e) Pre-test the make-up tank contained 50 ppm potassium and 14 ppm hydrazine, the surge tank 3 ppm oxygen and 4 ppm hydrazine and the primary loop <5 ppb oxygen and 0.01 ppm hydrazine.

TABLE 5-30

SAMPLE LINE FLOW RATES, TEST 15 (T-2050 to T-2054)

Primary		Model Boiler				SORV Condensate	
		S-1		IKP-4			
Run Time (min)	Flow Rate (ml/mm)	Run Time (min)	Flow Rate (ml/min)	Run Time (min)	Flow Rate (ml/min)	Run Time (min)	Flow Rate (ml/min)
-4	94	-6	94	-5	82	-7	833
14	84	12	90	13	76	11	811
28	88	27	66	27	76	26	833
43	86	42	70	43	72	41	882
53	84	57	70	53	64	57	833
74	83	72	66	73	44	71	800
133	64	132	69	133	36	131	811
142	108	135	92	136	100	-	-
163	68	162	92	162	74	161	833
183	66	181	92	182	71	181	870
203	63	202	88	202	52	201	811
-	-	-	-	214	98	-	-
228	64	227	88	231	98	226	833
258	62	257	90	258	87	256	833
272	54	271	90	272	100	271	857
289	56	288	91	289	118	287	811
-	-	-	-	291	116	-	-
307	54	306	85	307	110	305	833
322	54	322	85	322	111	321	833
-	-	323	84	-	-	-	-
347	53	346	80	347	113	345	857
363	53	361	80	362	105	361	833
382	52	381	80	382	108	380	857
402	52	401	78	402	108	401	833
422	51	421	76	422	100	421	833
448	52	447	76	448	100	447	811
468	50	466	65	467	102	465	811
493	51	491	61	492	102	491	811

Notes: (a) Blowdown commenced at 10 minutes, SGTRs at 151, 260, 365 and 450 minutes respectively.

(b) Primary, S-1 and IKP-4 flows adjusted after 134 minutes; IKP-4 flow adjusted 213 minutes.

TABLE 5-31

ANALYTICAL RESULTS, TEST 16 (T-2061 to T-2065)

Run Time (min)	Primary			Model Boiler						SOSV Condensate		
				S-1			IKF-4					
	Li (ppb)	K (ppm)	Conductivity (µS/cm)	Li (ppm)	K (ppm)	Conductivity (µS/cm)	Li (ppm)	K (ppm)	Conductivity (µS/cm)	Li (ppb)	K (ppb)	Resistivity (MΩ cm)
-30	-	-	360	-	-	1600	-	-	1800	-	-	0.110
-20	-	-	360	-	-	1530	-	-	1650	-	-	0.095
-10	-	-	358	-	-	1350	-	-	1500	-	-	0.085
0	-	-	358	59	0.460	1177	51	0.450	1317	0.6	1.2	0.077
10	-	-	359	59	0.460	1089	48	0.460	1128	0.6	~0	0.105
15	-	-	359	53	0.400	918	53	0.450	1130	0.6	1.0	0.105
20	-	-	360	45	0.340	685	49	0.450	1055	0.4	0.6	0.100
25	-	-	360	39	0.300	550	46	0.410	906	0.3	0.5	0.098
30	-	-	360	34	0.250	418	41	0.380	766	~0	0.4	0.096
35	-	-	361	27	0.200	330	36	0.340	636	0.4	3.0	0.096
40	-	-	361	23	0.160	271	32	0.290	526	~0.2	2.4	0.098
45	-	-	361	20	0.150	236	26	0.260	444	~0.2	4.0	0.102
50	-	-	361	5	0.040	45	26	0.240	400	4.0	~0	0.113
52.5	-	-	358	-	-	24	-	-	382	3.0	1.2	0.085
55	-	-	354	0.620	0.0044	23	24	0.220	375	7.8	0.4	0.064
60	-	-	345	-	-	17	33	0.330	495	13.8	0.4	0.060
65	-	-	335	0.270	0,0024	14	-	-	484	40	0.8	0.065
70	-	-	334	-	-	14	16	0.200	285	30	~0	0.063
75	-	-	334	-	-	15	-	-	180	40	~0	0.064
80	2.8	53	335	0.100	0.0010	15	7	0.130	120	20	~0	0.064
95	-	-	335	0.065	0.0010	16	0.600	0.040	35	10.0	0.6	0.088
110	7.6	56	336	0.060	0.0006	15	0.240	0.020	30	8.0	~0	0.063
130	-	-	337	0.050	0.0006	17	0.130	0.020	29	5.8	~0	0.062
135	-	-	337	0.045	0.0005	15	0.130	0.280	29	5.8	0.4	0.062
138	-	-	338	-	-	18	-	-	28	15	5.8	0.053
140	7.2	56	337	0.055	0.100	24	0.130	0.190	28	20	15.6	0.045
145	-	-	318	0.050	0.130	25	3	63	266	5.4	10.4	0.044
150	-	-	305	-	-	25	-	-	686	4.2	14.0	0.044
155	-	-	296	0.045	0.230	25	6	260	978	4.4	20	0.044
165	-	-	273	0.040	0.300	24	6	380	1471	3.0	35	0.046
170	6.2	57	268	-	-	17	-	-	1598	-	-	0.059
175	-	-	268	0.030	0.380	16	3	335	1272	2.4	50	0.061
185	-	-	265	0.030	0.280	17	1.5	175	586	2.4	50	0.060
190	-	-	263	-	-	17	-	-	368	2.4	50	0.060
193	-	-	262	-	-	16	-	-	337	7.0	110	0.061
195	-	-	261	0.030	0.600	16	1.5	145	556	6.8	80	0.060
200	7.2	59	260	-	-	16	-	-	1206	80	1260	0.062
215	-	-	258	0.040	0.250	16	16	200	790	40	680	0.060
230	5.8	59	257	0.060	0.260	17	10	195	440	20	250	0.058
240	-	-	257	0.040	0.240	17	8	75	349	12.0	220	0.058
243	-	-	257	-	-	17	-	-	312	20	760	0.052
245	-	-	257	0.035	0.230	22	6	100	278	20	560	0.044
250	-	-	256	0.030	0.250	24	5	52	257	20.8	650	0.042
255	-	-	250	-	-	24	-	-	423	16.6	550	0.043
260	5.6	59	244	0.025	0.380	24	6	166	650	14.0	650	0.044
265	-	-	239	-	-	24	-	-	774	12.0	550	0.044
270	-	-	230	0.020	0.400	24	6	230	876	10.2	630	0.044
280	-	-	225	0.025	0.530	17	7	310	1209	7.6	650	0.059
290	5.2	59	224	0.020	0.430	17	7	280	1020	8.0	770	0.060
295	-	-	224	7	150	392	-	-	798	40	1220	0.062

179

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TABLE 5-31 (CONTINUED)

ANALYTICAL RESULTS, TEST 16 (T-2061 to T-2065)

Run Time (min)	Primary			Model Boiler						SORV Condensate		
				S-1			IKP-4					
	Li (ppb)	K (ppm)	Conductivity (µS/cm)	Li (ppm)	K (ppm)	Conductivity (µS/cm)	Li (ppm)	K (ppm)	Conductivity (µS/cm)	Li (ppb)	K (ppb)	Resistivity (MΩ cm)
300	-	-	223	-	-	511	12	235	924	50	300	0.061
305	-	-	223	8	136	460	-	-	990	50	150	0.066
320	5.2	59	223	8	136	596	16	250	1079	30	100	0.070
325	-	-	223	-	-	675	-	-	1151	20	100	0.065
330	-	-	223	7	124	630	16	245	1282	19.6	120	0.042
335	-	-	224	-	-	889	-	-	1431	16.0	90	0.041
340	-	-	221	7	144	776	17	265	1590	14.4	80	0.042
350	5.8	59	216	9	240	1193	18	300	1937	11.4	60	0.052
360	-	-	211	9	260	1284	18	330	2108	7.6	60	0.072
370	-	-	210	8	225	1046	18	325	2157	8.0	80	0.075
380	5.0	59	210	9	255	1254	17	310	1876	6.0	60	0.066
385	-	-	210	-	-	995	-	-	1461	6.2	40	0.067
395	-	-	210	7	195	952	11	205	1277	6.6	40	0.073
400	-	-	210	-	-	953	-	-	1290	6.4	40	0.074
405	-	-	210	7	200	972	11	215	1302	7.0	40	0.060
410	5.0	60	210	-	-	1002	-	-	1314	6.0	40	0.057
415	-	-	208	7	205	1032	11	225	1339	6.0	40	0.058
420	-	-	206	-	-	1069	-	-	1387	5.4	30	0.059
425	-	-	206	7	230	1119	11	260	1473	5.0	30	0.053
435	-	-	203	7	250	1216	11	260	1546	4.4	20	0.073
440	4.4	60	203	-	-	1266	-	-	1656	-	-	0.074
445	-	-	203	7	255	1297	11	285	1705	3.0	20	0.073
450	-	-	203	-	-	1340	-	-	1717	-	-	0.073

Notes:

(a) SGTRs extended from 135 to 165, 240 to 270, 325 to 355 and 400 to 430 minutes, blowdown extended from 10 to 59 minutes.

(b) Conductivity and resistivity data taken from the computer outputs for the periods 0 to 75, 130 to 200, 235 to 300, 320 to 385 and 395 to 450 minutes.

(c) All SORV condensate analyses, except as noted below, all lithium analyses on primary samples and potassium analyses on S-1 samples (55 to 135 minutes) were carried out using the 0-20 ppb ranges. Precision ±0.1 to 0.3 ppb. The SORV condensate sample after 250 minutes was analysed using this range after dilution 1:2.

(d) All other analyses were carried out using the 0-1000 ppb ranges, mainly undiluted, precision ±2 to 12 ppb, or diluted 1:2 (SORV condensate samples for potassium at 200 and 295 minutes), 1:100 (lithium analyses on S-1 samples at 0 to 50 and 295 to 445 minutes and IKP-4 samples at 0 to 80 and 145 to 445 minutes, potassium analyses on primary samples and on the IKP-4 sample at 145 minutes), 1:200 (potassium analyses on S-1 samples at 295 to 340 minutes and IKP-4 samples at 250 to 260 minutes) or 1:500 (potassium analyses on S-1 samples at 350 to 445 minutes and IKP-4 samples at 155 to 245 and 270 to 445 minutes).

(e) Pre-test the make-up tank contained ~60 ppm potassium, ~2 ppm oxygen and 10 ppm hydrazine, the surge tank 2 ppm oxygen and ~5 ppm hydrazine and the primary loop <5 ppb oxygen and 0.01 ppm hydrazine.

TABLE 5-32

SAMPLE LINE FLOW RATES, TEST 16 (T-2061 to T-2065)

Primary		Model Boiler				SORV Condensate	
		S-1		IKP-4			
Run Time (min)	Flow Rate (ml/min)	Run Time (min)	Flow Rate (ml/min)	Run Time (min)	Flow Rate (ml/min)	Run Time (min)	Flow Rate (ml/min)
3	118	2	104	2	74	1	811
22	116	21	70	21	74	20	857
43	116	42	66	43	68	41	833
57	116	56	64	57	50	56	857
-	-	-	-	66	20	-	-
78	116	69	84	69	89	71	811
88	114	81	82	87	50	85	833
-	-	-	-	88	131	-	-
112	112	111	88	112	59	110	811
-	-	-	-	117	90	-	-
132	108	131	84	132	72	130	811
149	108	148	90	148	60	147	811
168	106	166	88	167	44	166	833
-	-	-	-	171	102	-	-
-	-	-	-	182	68	-	-
187	106	186	86	187	38	185	811
-	-	-	-	190	108	-	-
200	102	197	86	197	43	196	811
-	-	-	-	201	100	-	-
216	104	216	87	216	58	215	857
234	106	232	82	233	58	232	833
247	100	246	83	246	60	245	833
262	104	261	86	262	66	260	811
273	101	272	88	273	64	271	833
284	100	284	87	283	58	283	833
293	102	291	86	293	54	291	811
-	-	-	-	292	120	-	-
322	102	321	85	322	83	321	833
333	106	332	84	333	110	331	833
352	103	351	84	352	80	350	833
372	102	371	76	372	138	370	857
384	100	383	80	384	132	382	857
398	100	396	86	398	158	395	833
408	98	406	86	407	130	406	857
418	97	416	82	417	162	415	833
432	97	431	88	431	158	430	833
447	94	446	84	447	140	445	857

Notes: (a) Blowdown phase commenced at 10 minutes, SGTRs at 135, 240, 315 and 400 minutes respectively.

(b) S-1 flow adjusted after 67 minutes; IKP-4 flows adjusted after 67, 87, 114, 169, 188, 200 and 292 minutes.

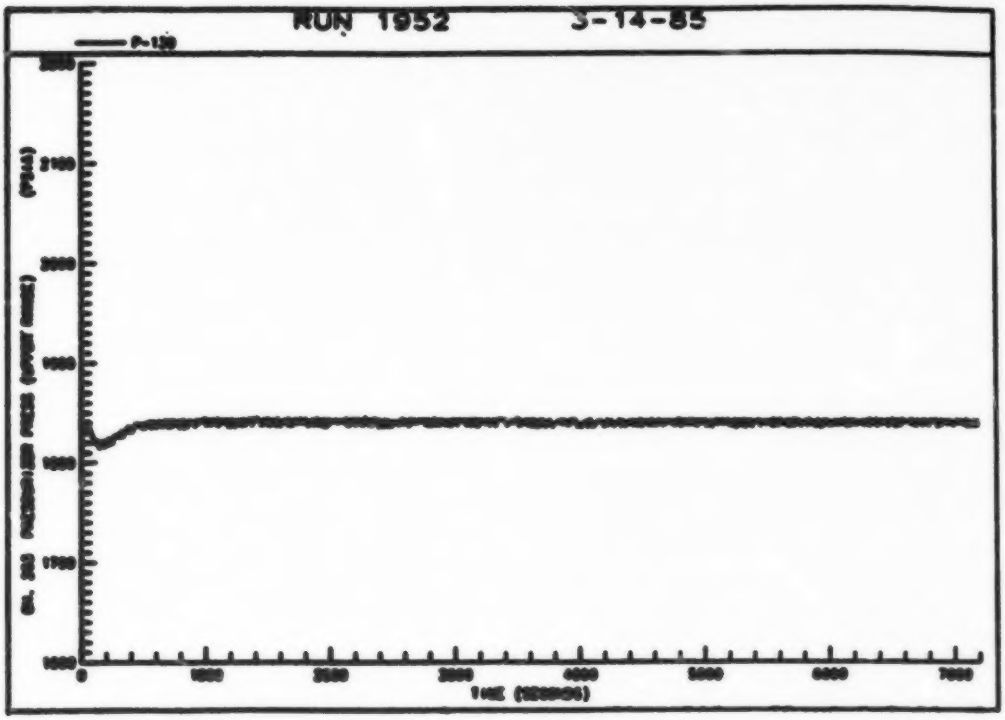

Figure 5-1. Primary System (Pressurizer) Pressure (P-139): Test No. 1 (T-1952)

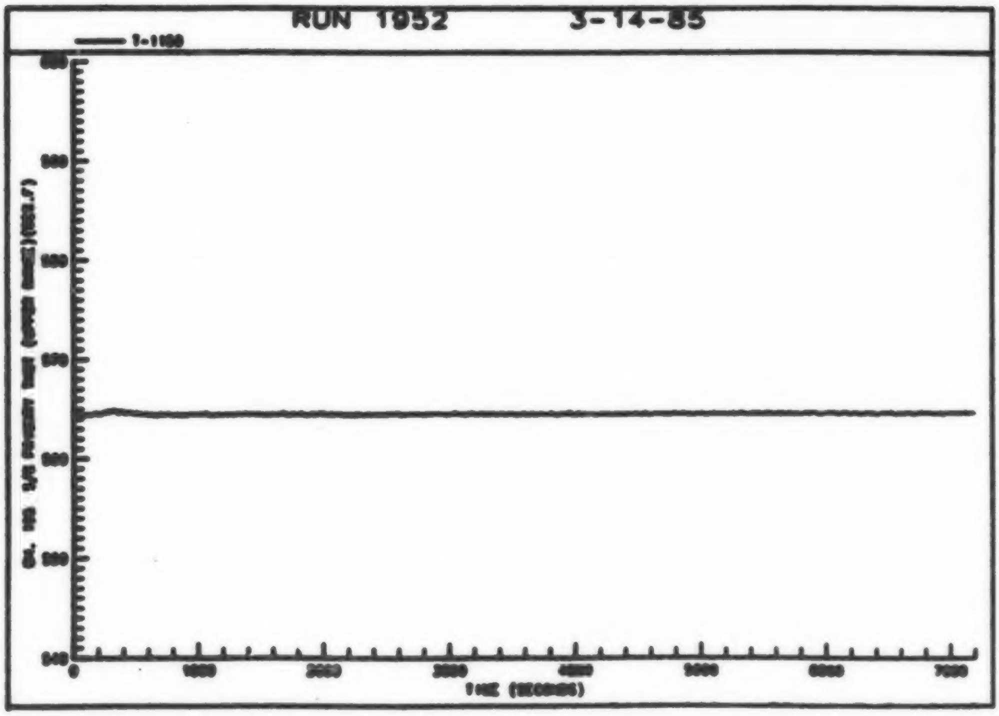

Figure 5-2. Primary Fluid T_{hot} (T-1150): Test No. 1 (T-1952)

182

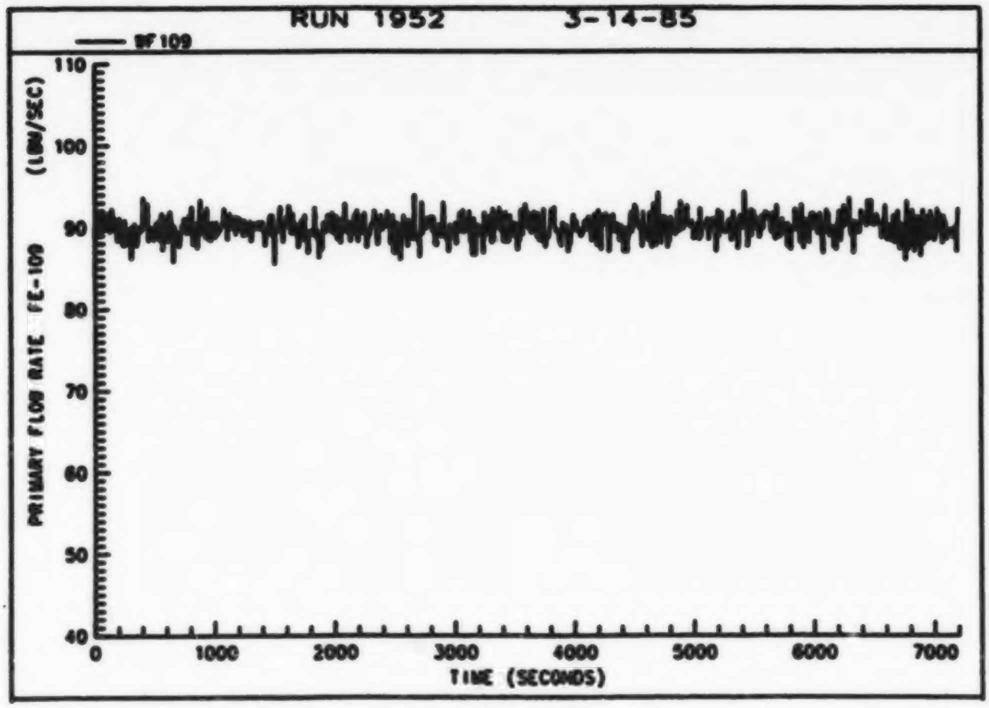

Figure 5-3. Primary Fluid Flow Rate (WF-109): Test No. 1 (T-1952)

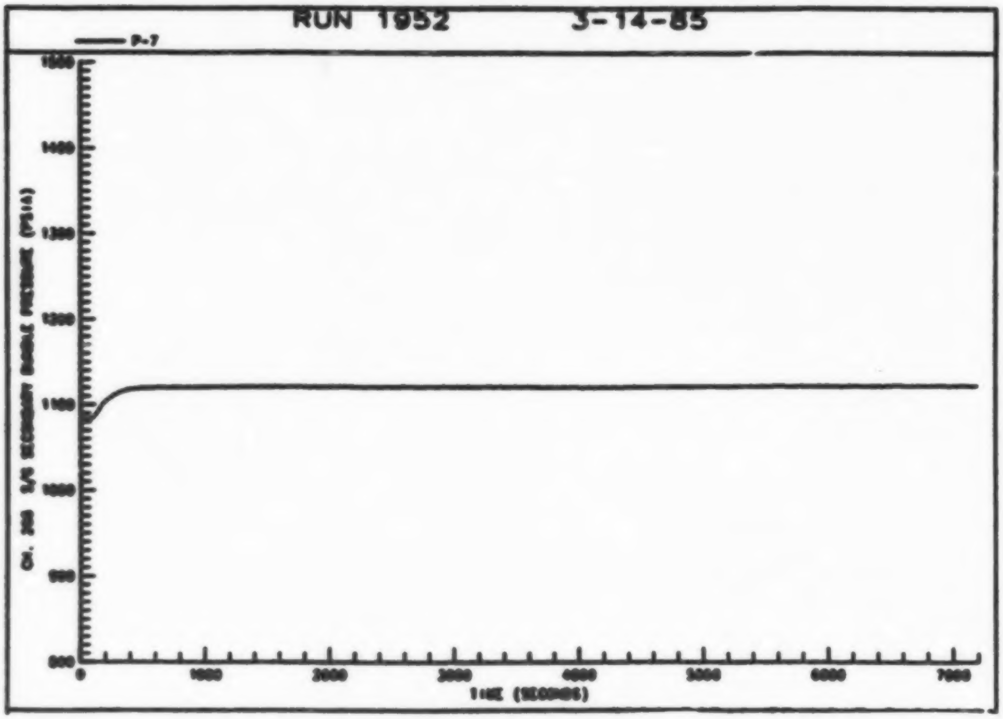

Figure 5-4. Secondary Side Pressure (P-7): Test No. 1 (T-1952)

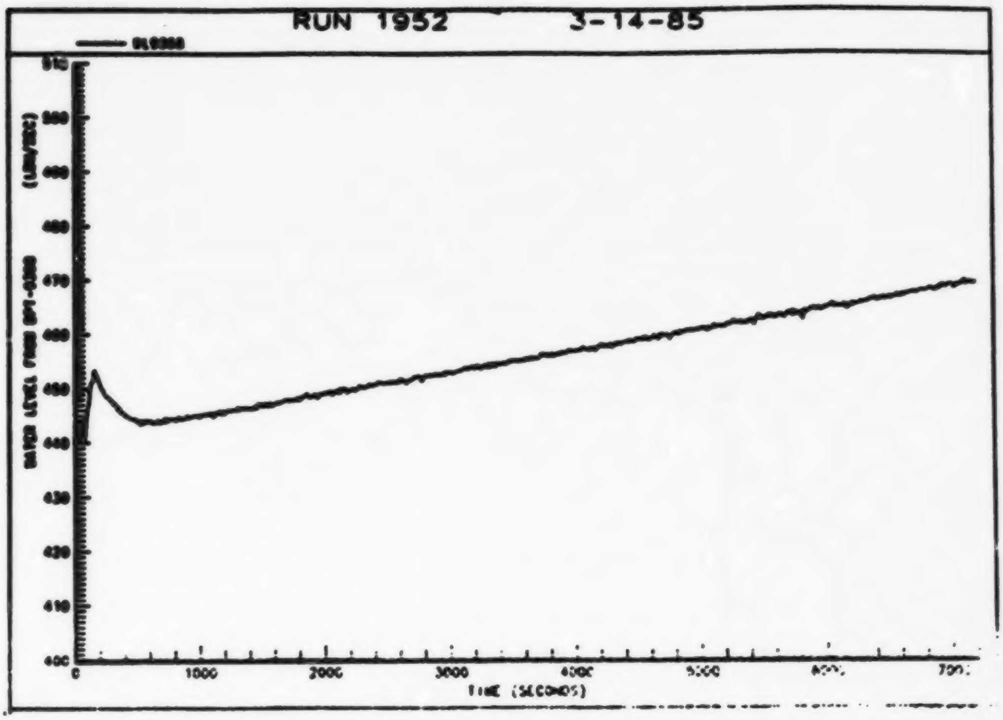

Figure 5-5. Downcomer Water Level - Narrow Range (WL-9368): Test No. 1 (T-1952)

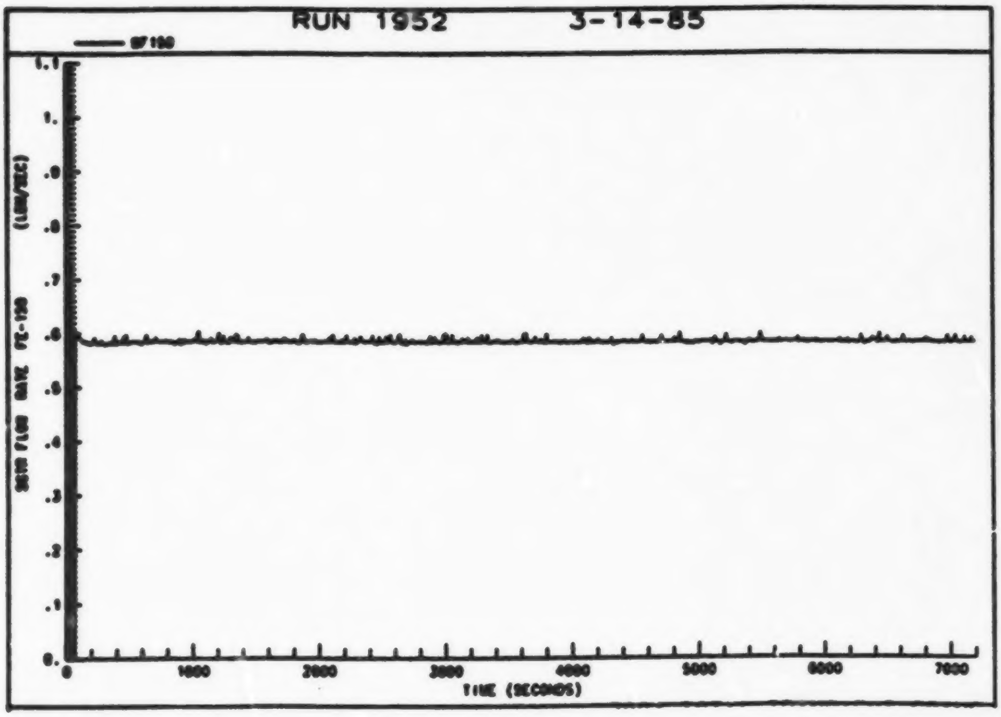

Figure 5-6. SGTR Flow Rate (WF-150): Test No. 1 (T-1952)

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184

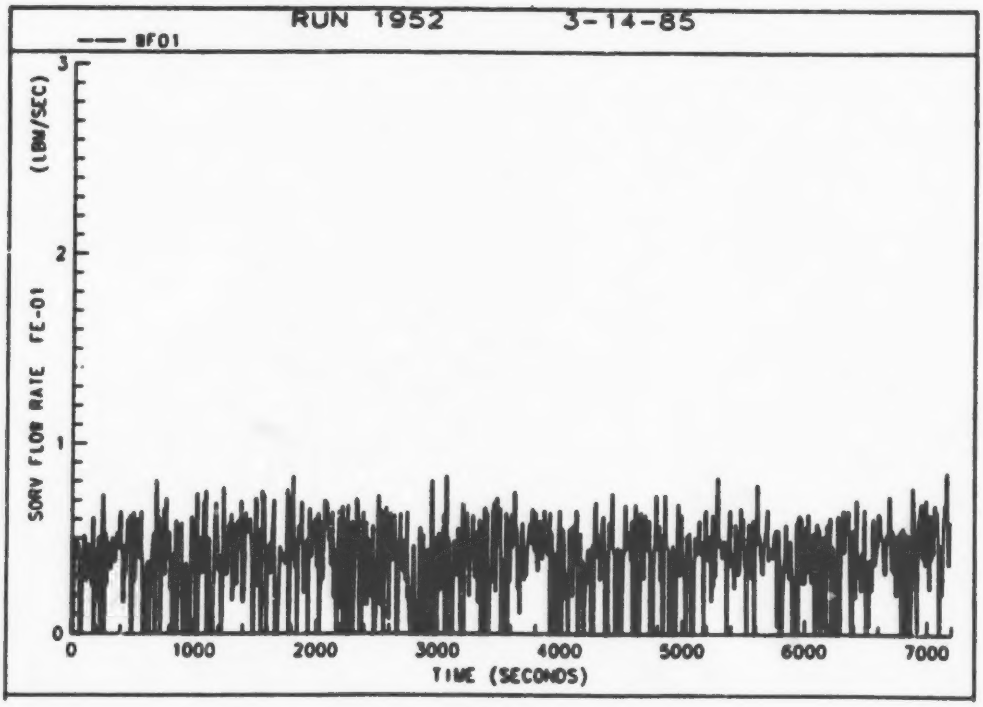

Figure 5-7. SORV Flow Rate (WF-01): Test No. 1 (T-1952)

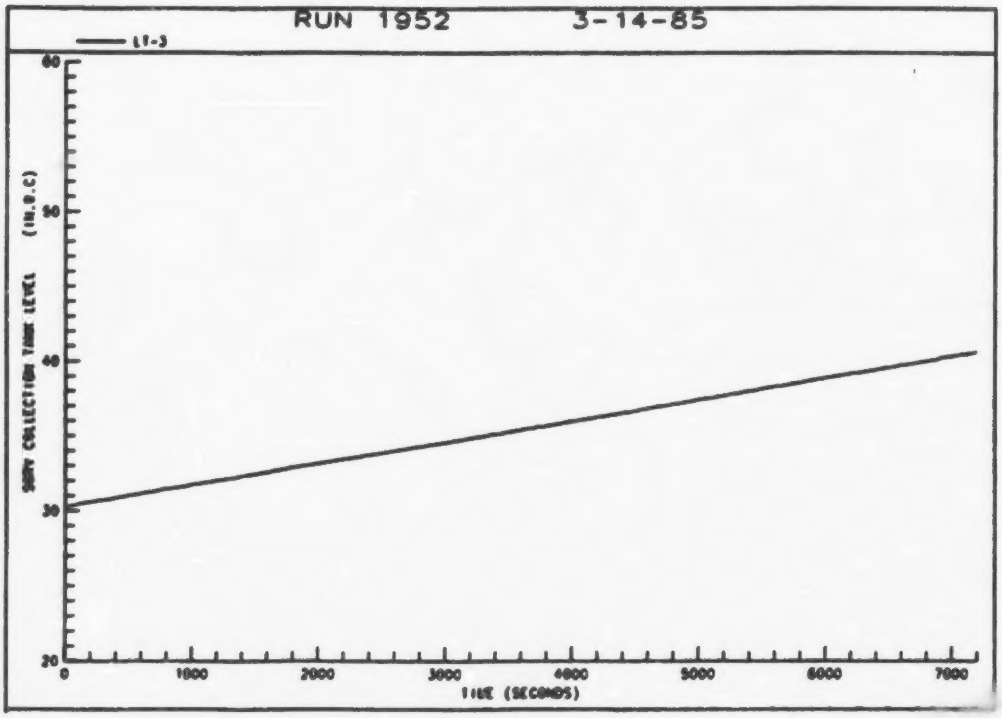

Figure 5-8. SORV Tank Level (LT-3): Test No. 1 (T-1952)

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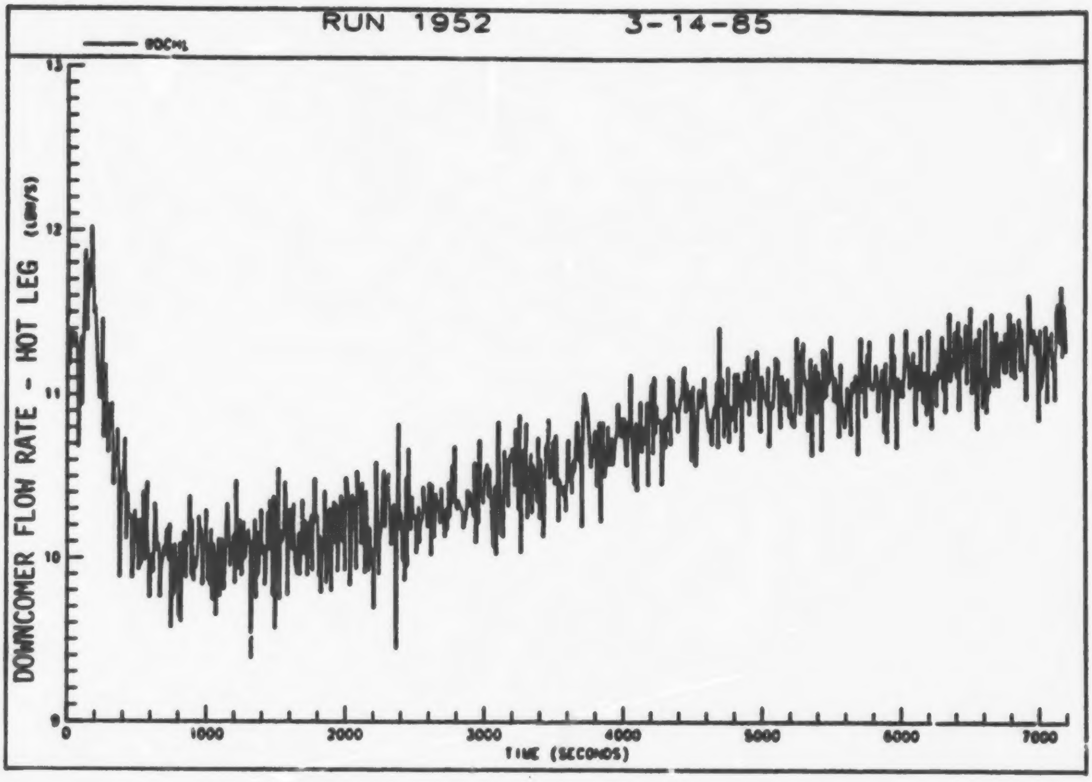

Figure 5-9. Hot Leg Downcomer Flow Rate (WDCHL): Test No. 1 (T-1952)

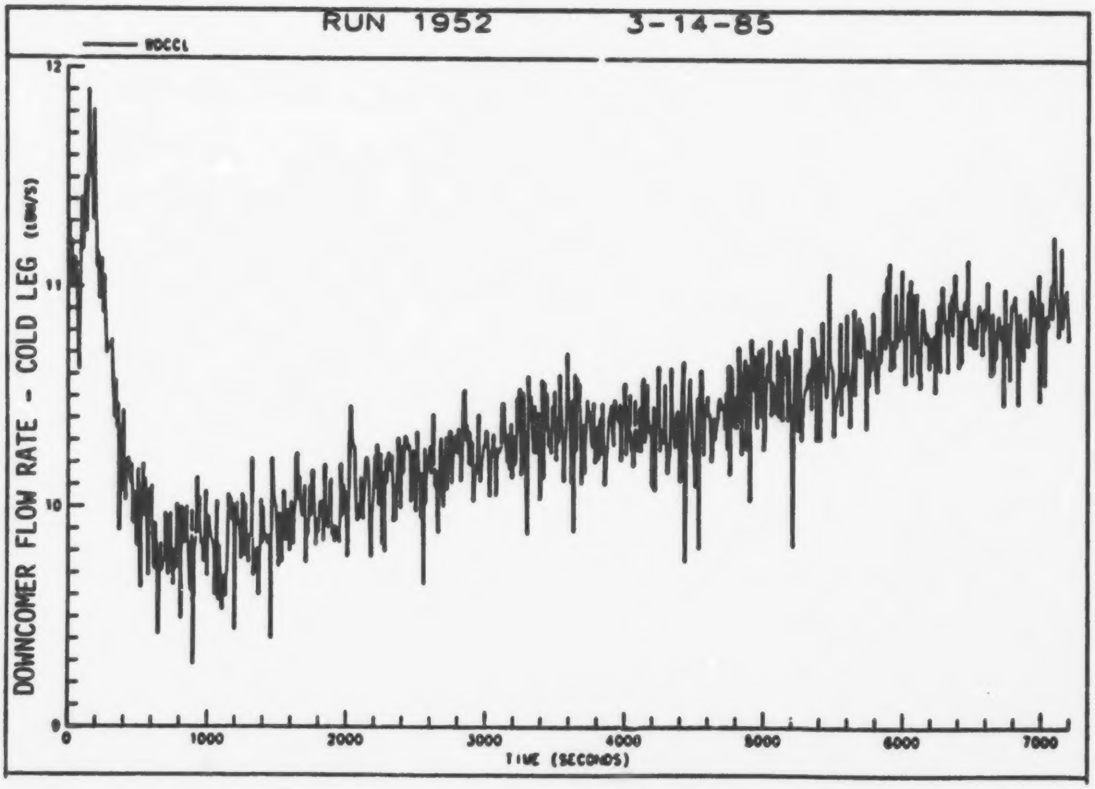

Figure 5-10. Cold Leg Downcomer Flow Rate (WDCCL): Test No. 1 (T-1952)

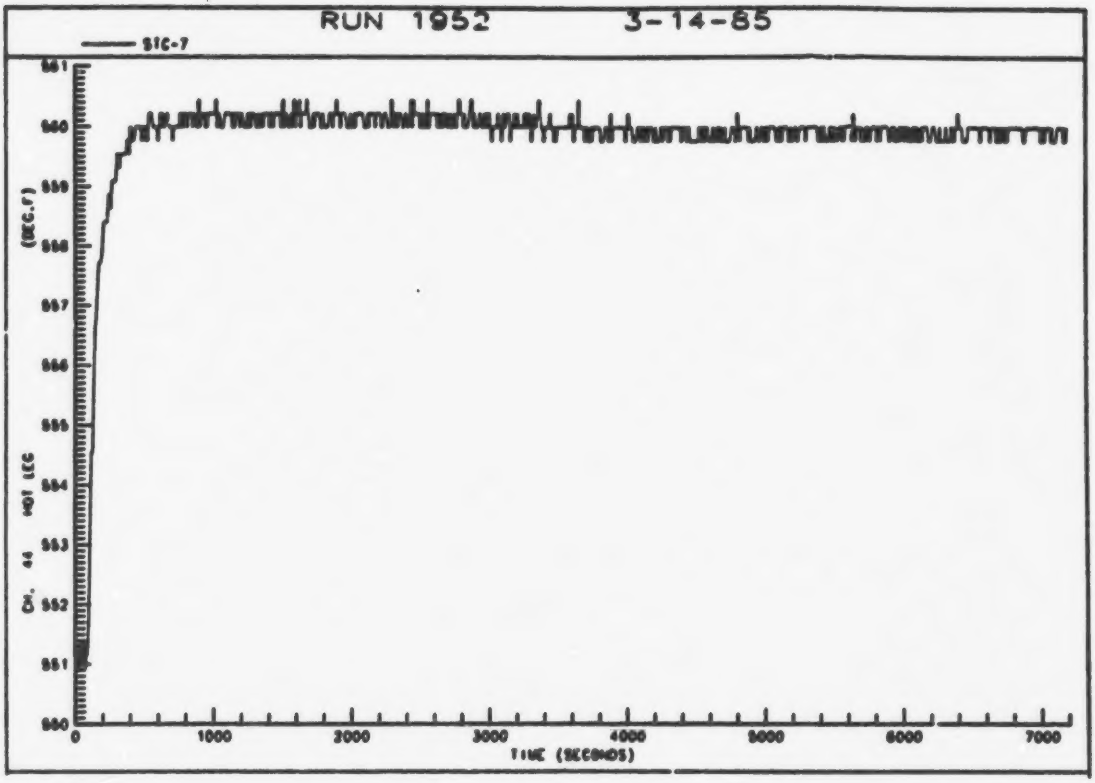

Figure 5-11. Secondary Fluid Temperature (STC-7): Test No. 1 (T-1952)

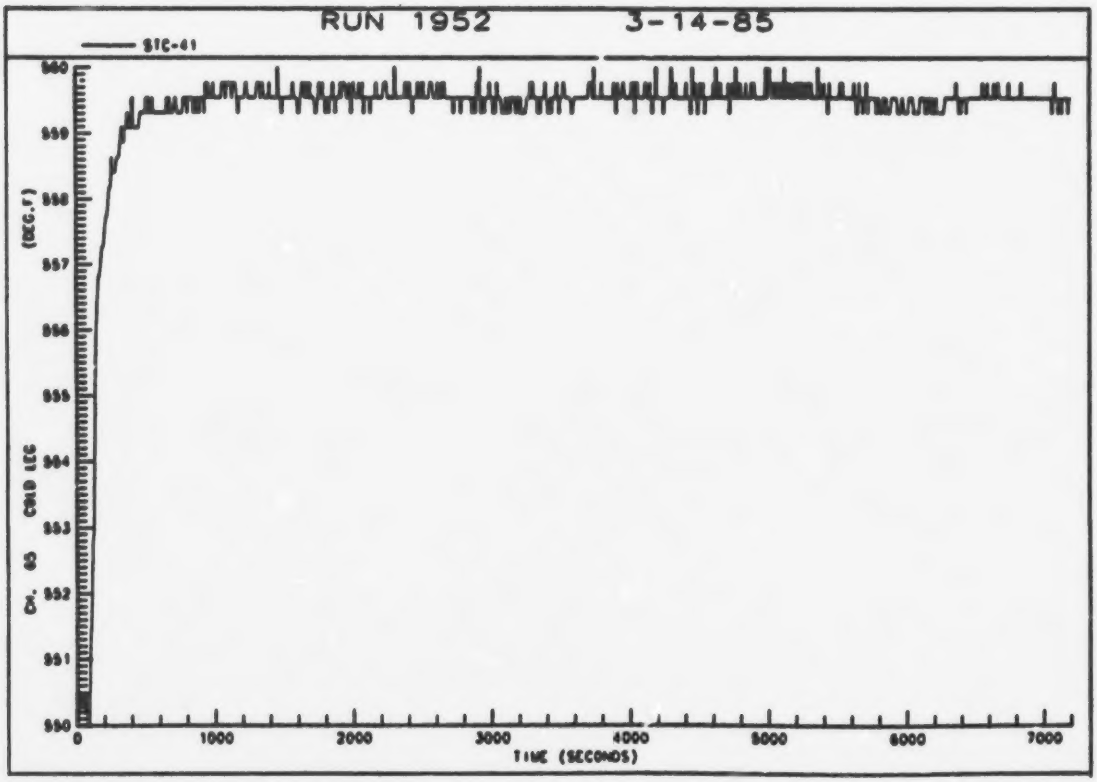

Figure 5-12. Secondary Fluid Temperature (STC-41): Test No. 1 (T-1952)

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187

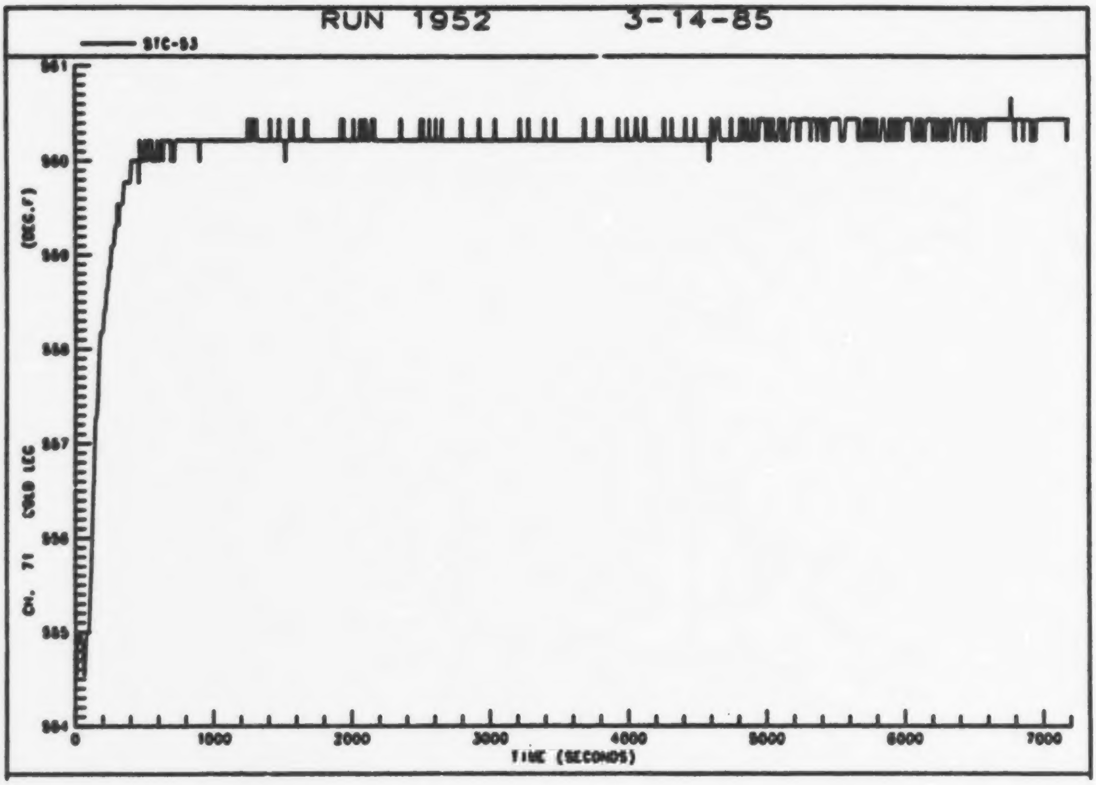

Figure 5-13. Secondary Fluid Temperature (STC-53): Test No. 1 (T-1952)

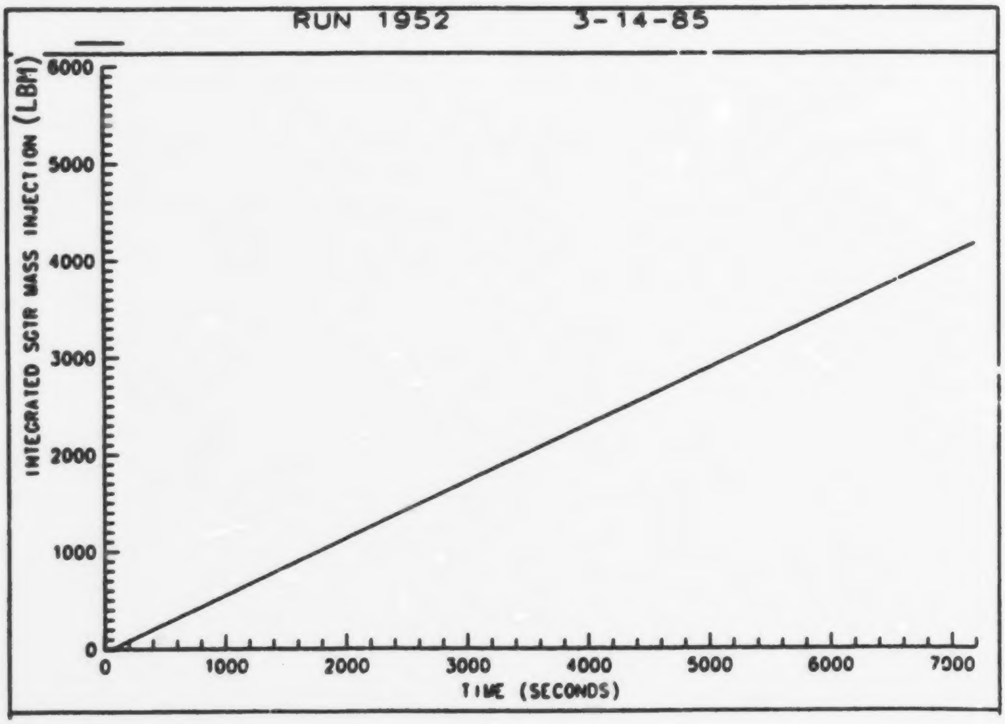

Figure 5-14. Integrated SGTR Flow: Test No. 1 (T-1952)

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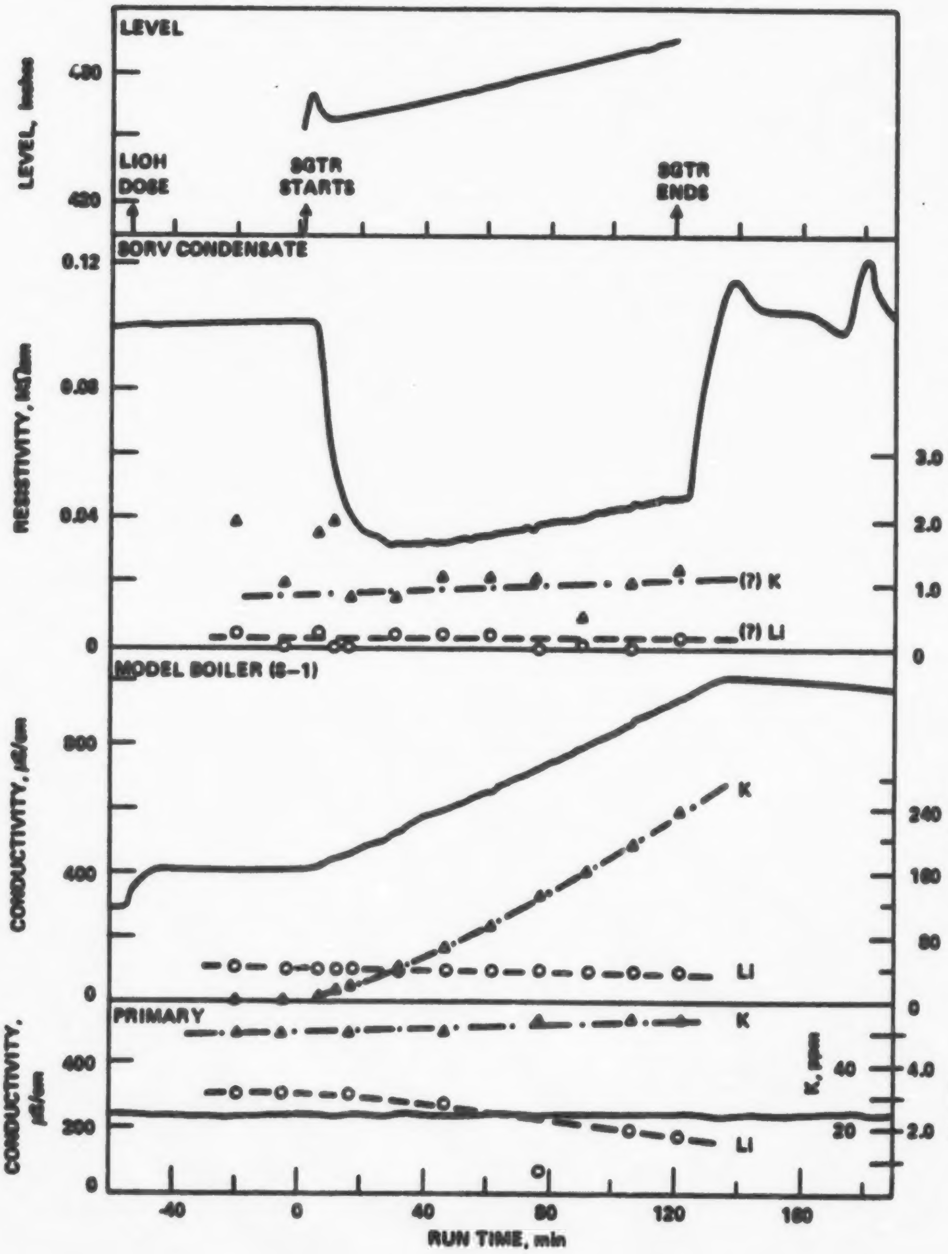

Figure 5-15. Variation in Tracer Concentrations: Test No. 1 (T-1952)

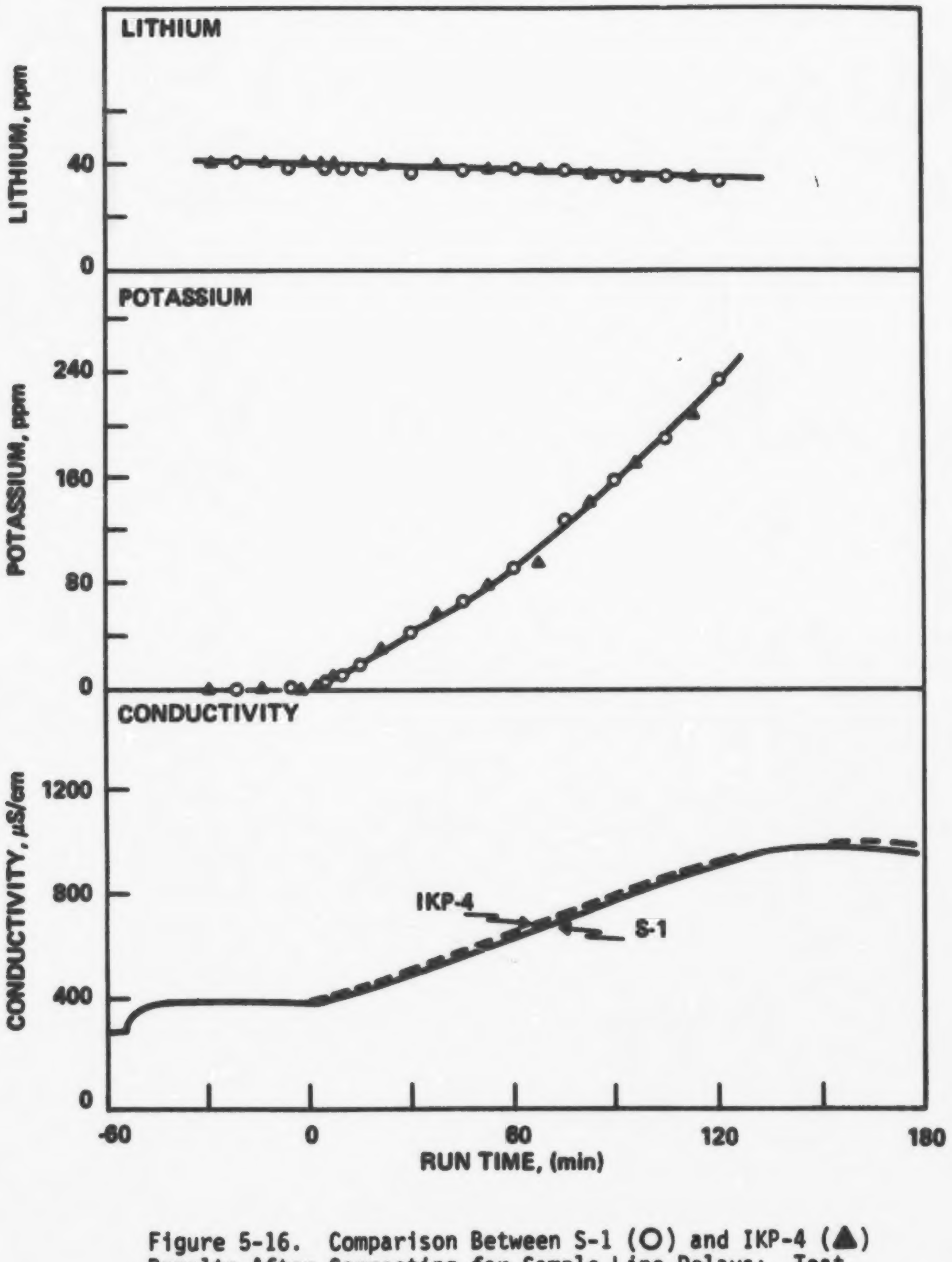

Figure 5-16. Comparison Between S-1 (○) and IKP-4 (▲) Results After Correcting for Sample Line Delays: Test No. 1 (T-1952)

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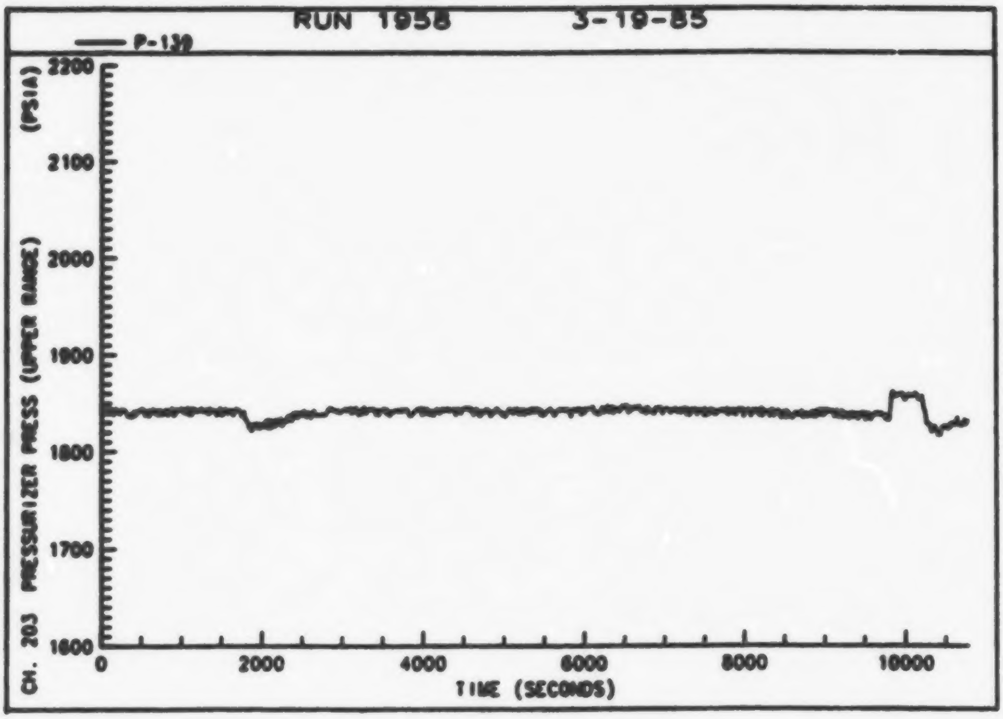

Figure 5-17. Primary System (Pressurizer) Pressure (P-139): Test No. 2 (T-1958)

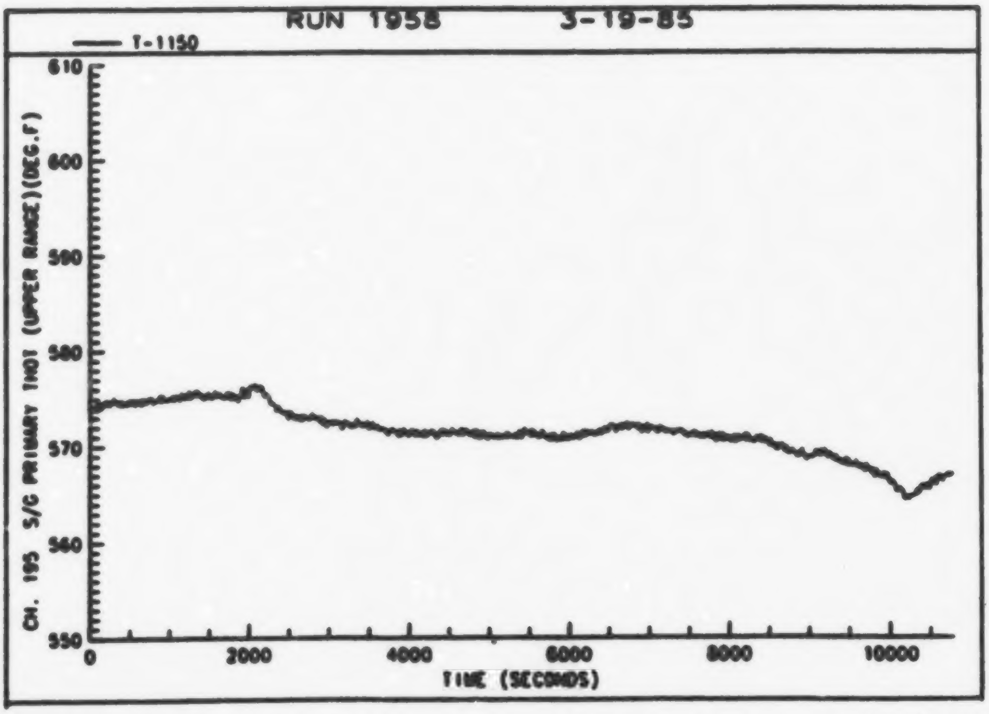

Figure 5-18. Primary Fluid T_{hot} (T-1150): Test No. 1 (T-1958)

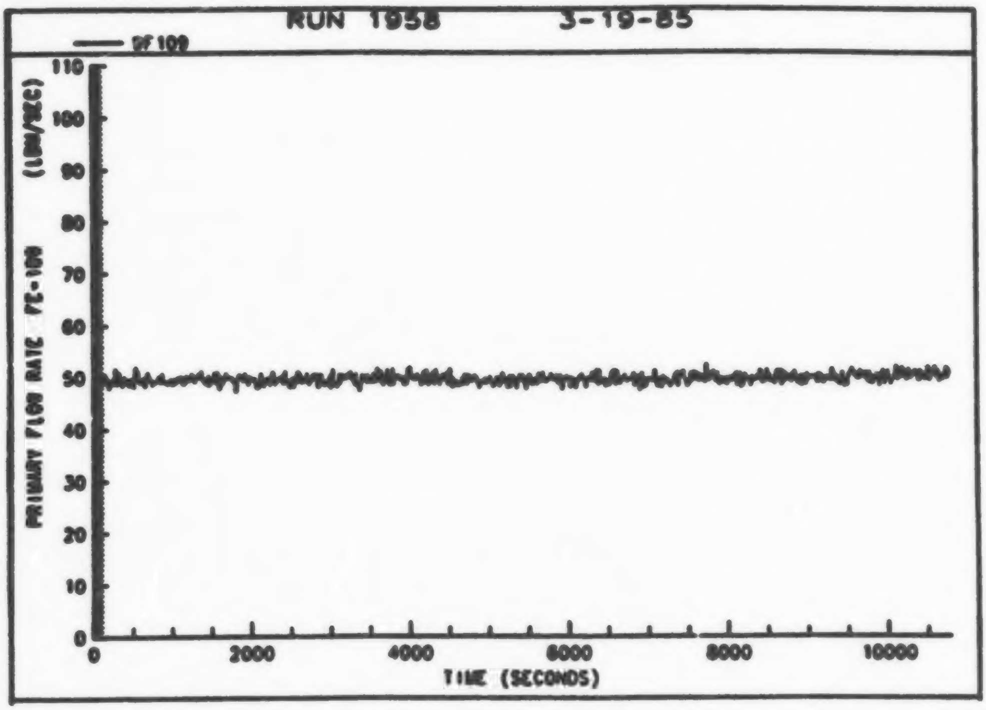

Figure 5-19. Primary Fluid Flow Rate (WF-109): Test No. 2 (T-1958)

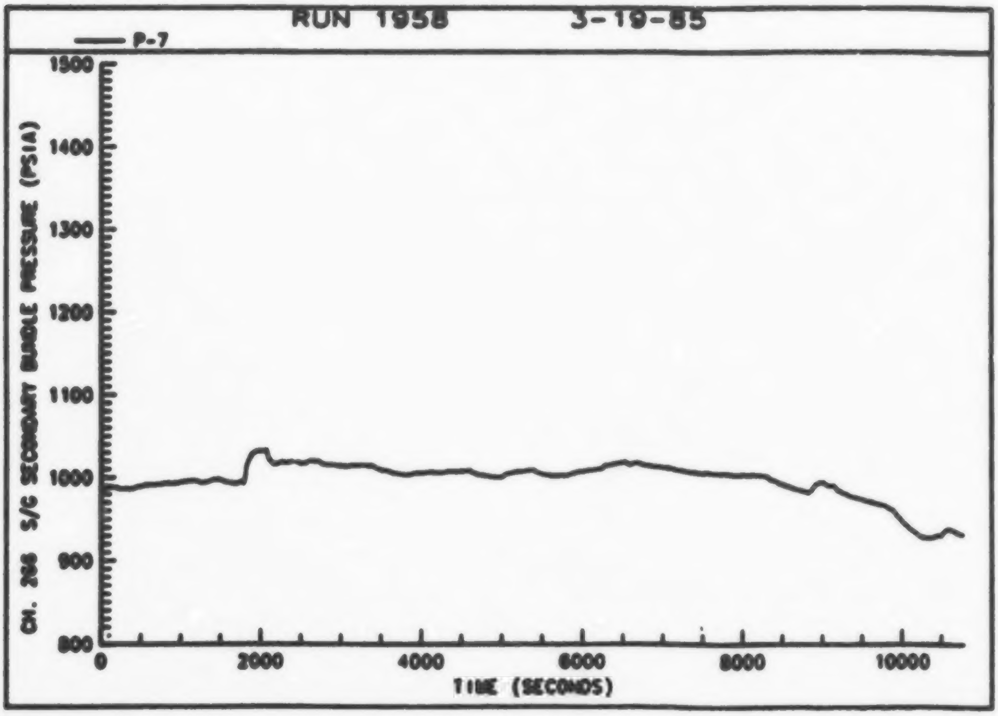

Figure 5-20. Secondary Side Pressure (P-7): Test No. 2 (T-1958)

192

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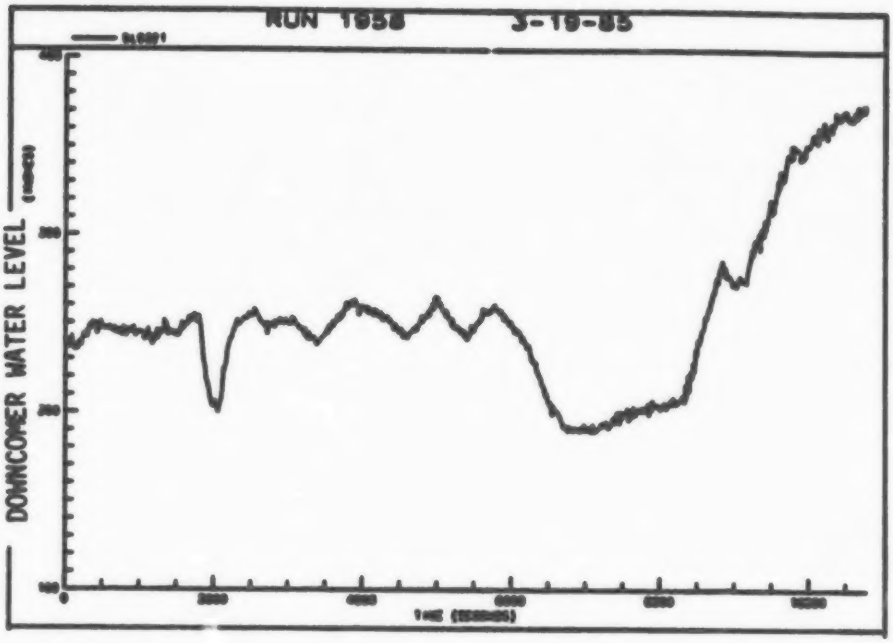

Figure 5-21. Downcomer Water Level - Wide Range (WL-9321): Test No. 2 (T-1958)

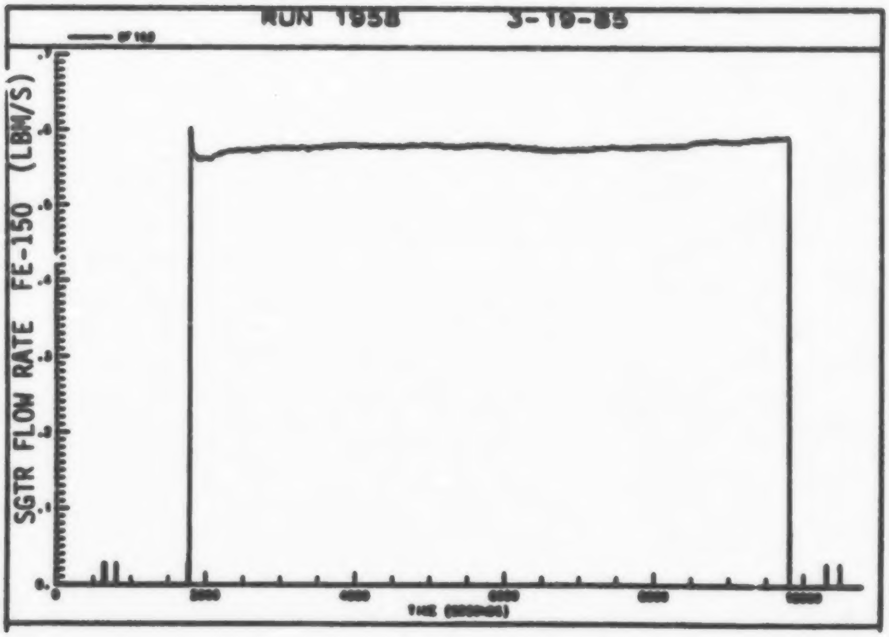

Figure 5-22. SGTR Flow Rate (WF-150): Test No. 2 (T-1958)

195

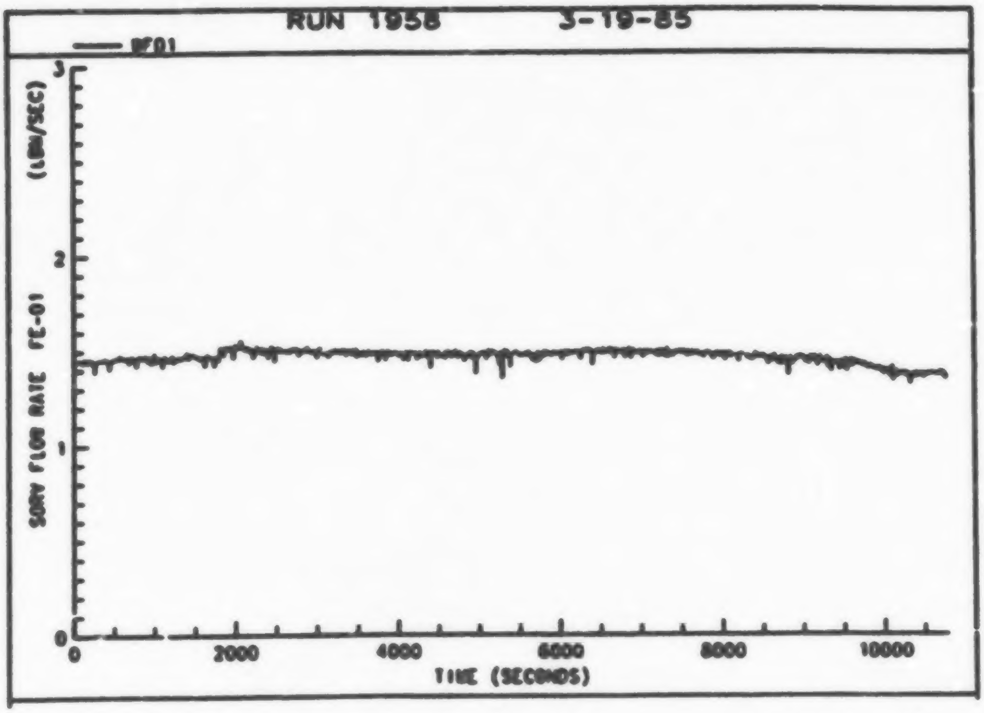

Figure 5-23. SORV Flow Rate (WF-01): Test No. 2 (T-1958)

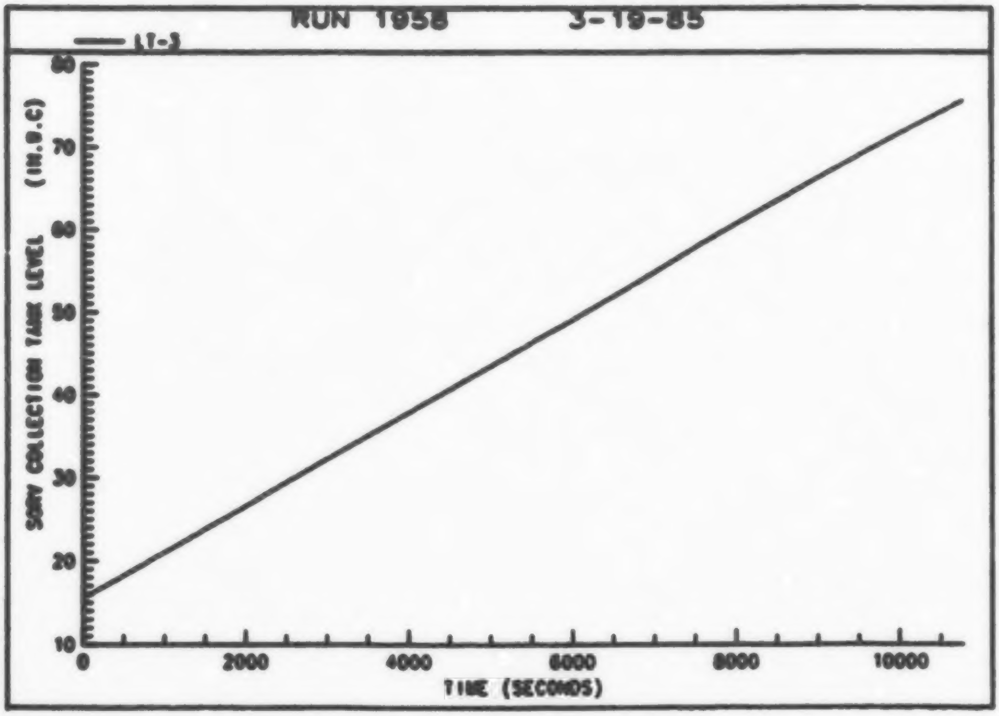

Figure 5-24. SORV Tank Level (LT-3): Test No. 2 (T-1958)

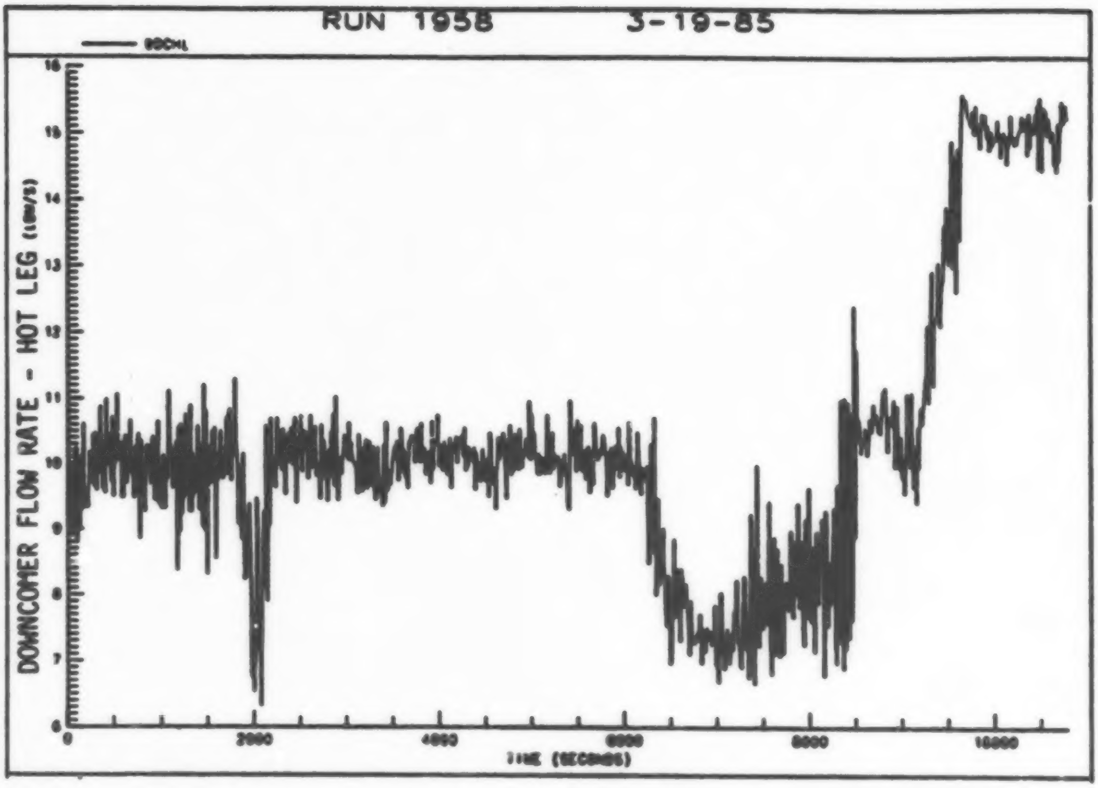

Figure 5-25. Hot Leg Downcomer Flow Rate (WDCHL): Test No. 2 (T-1958)

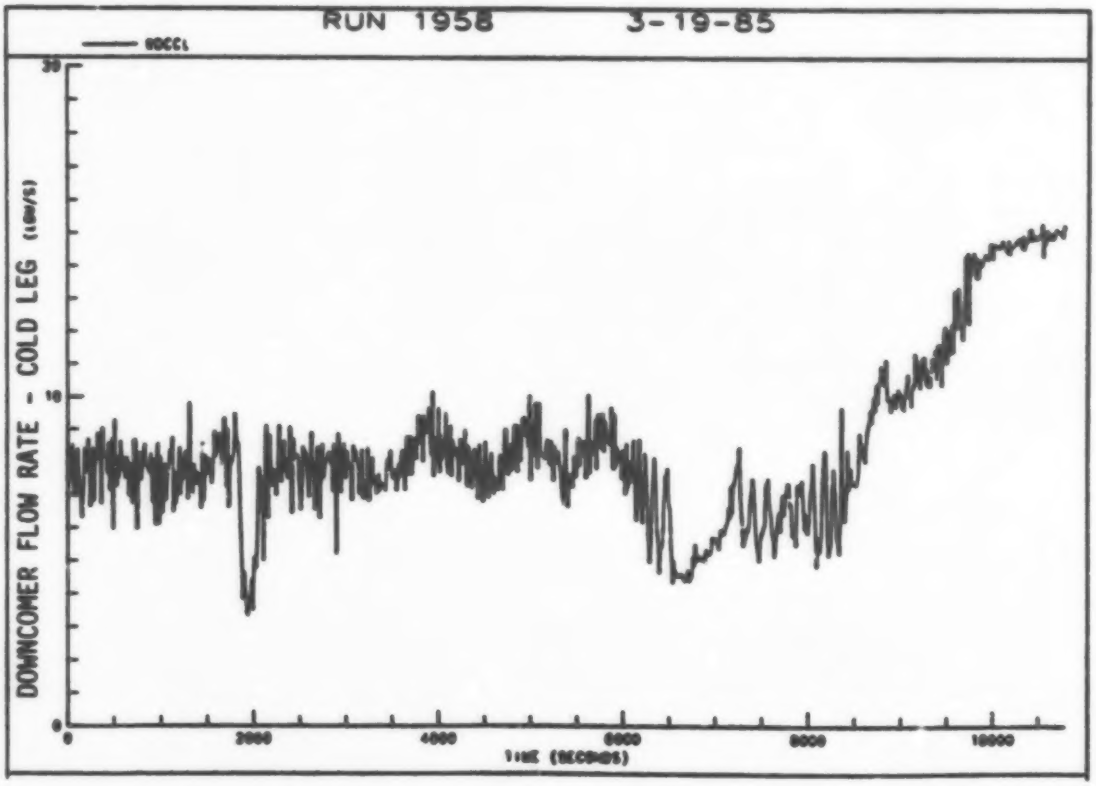

Figure 5-26. Cold Leg Downcomer Flow Rate (WDCCL): Test No. 2 (T-1958)

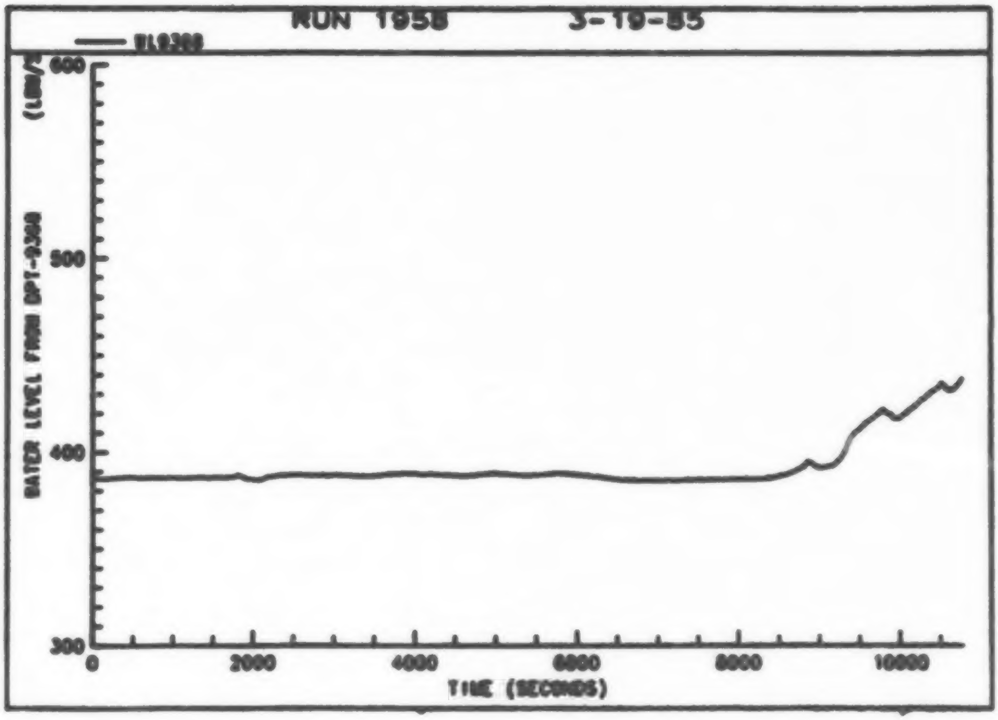

Figure 5-27. Downcomer Water Level - Narrow Range (WL-9368): Test No. 2 (T-1958)

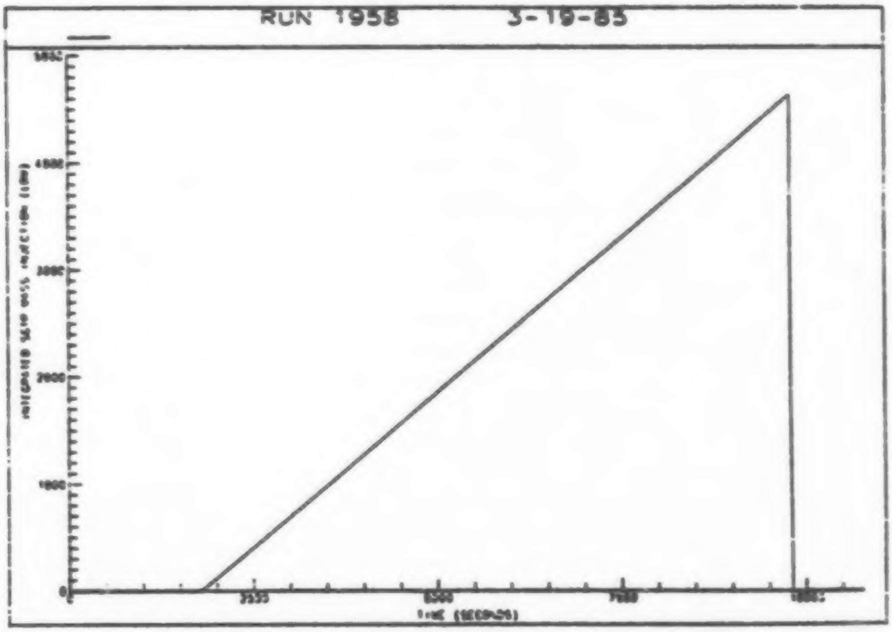

Figure 5-28. Integrated SGTR Flow: Test No. 2 (T-1958)

196

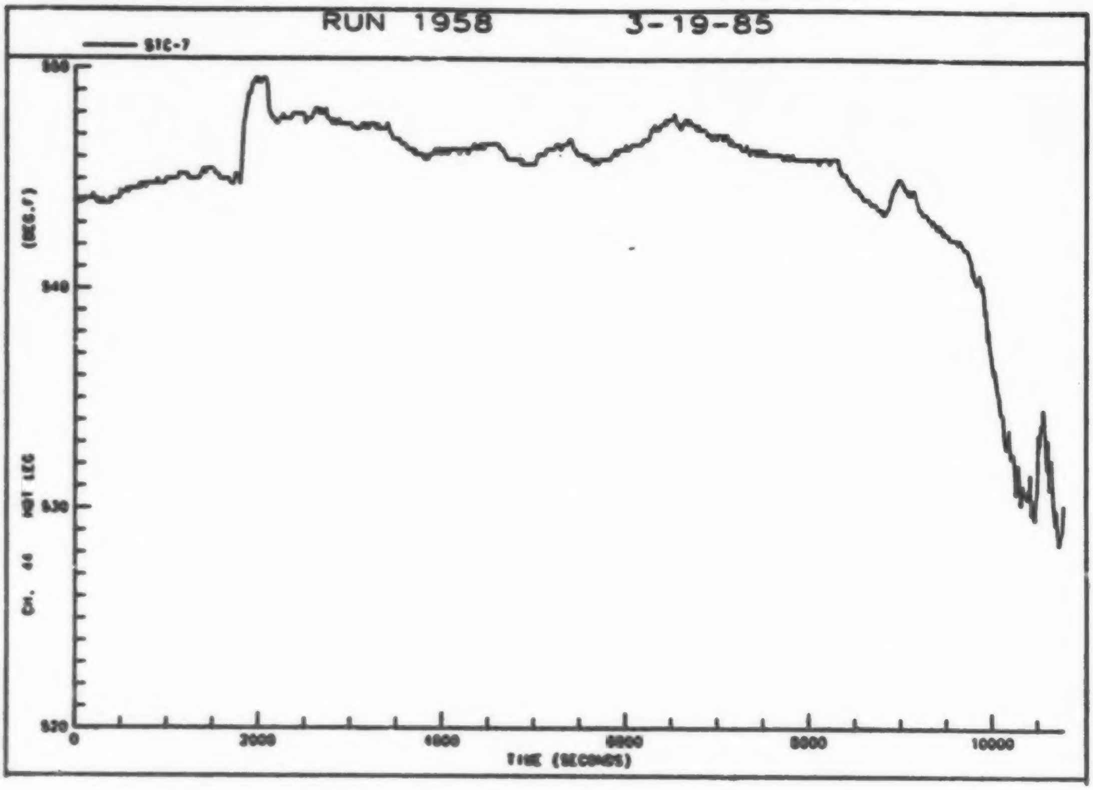

Figure 5-29. Secondary Fluid Temperature (STC-7): Test No. 2 (T-1958)

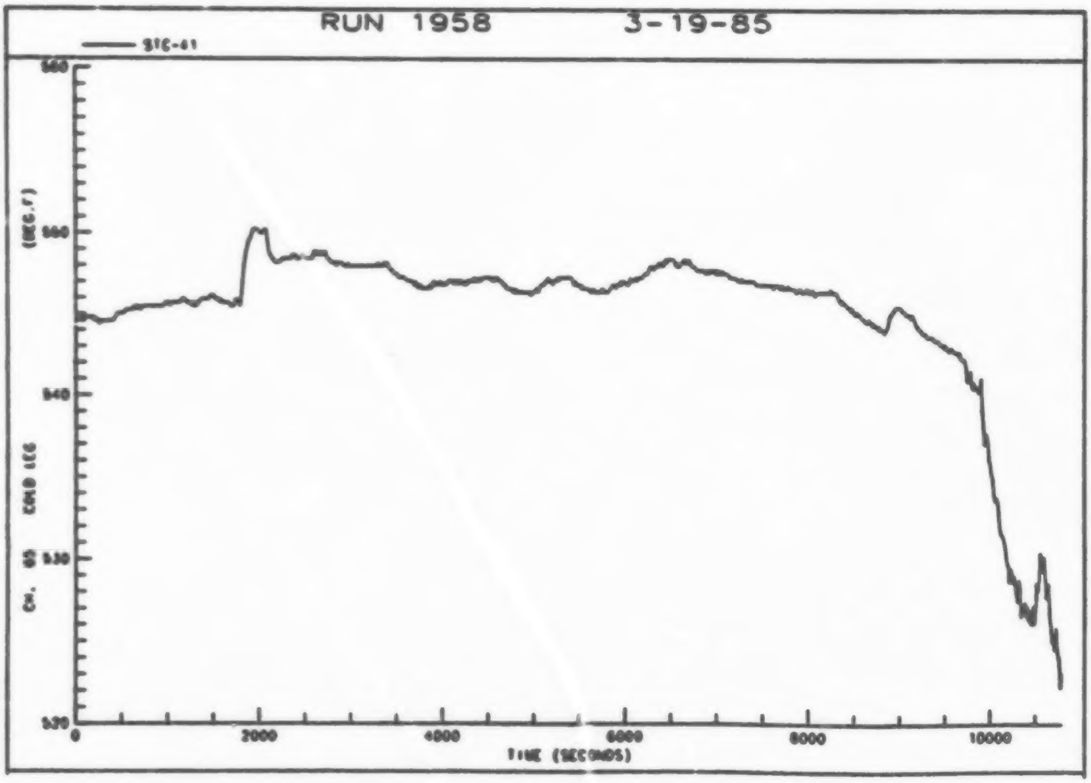

Figure 5-30. Secondary Fluid Temperature (STC-41): Test No. 2 (T-1958)

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197

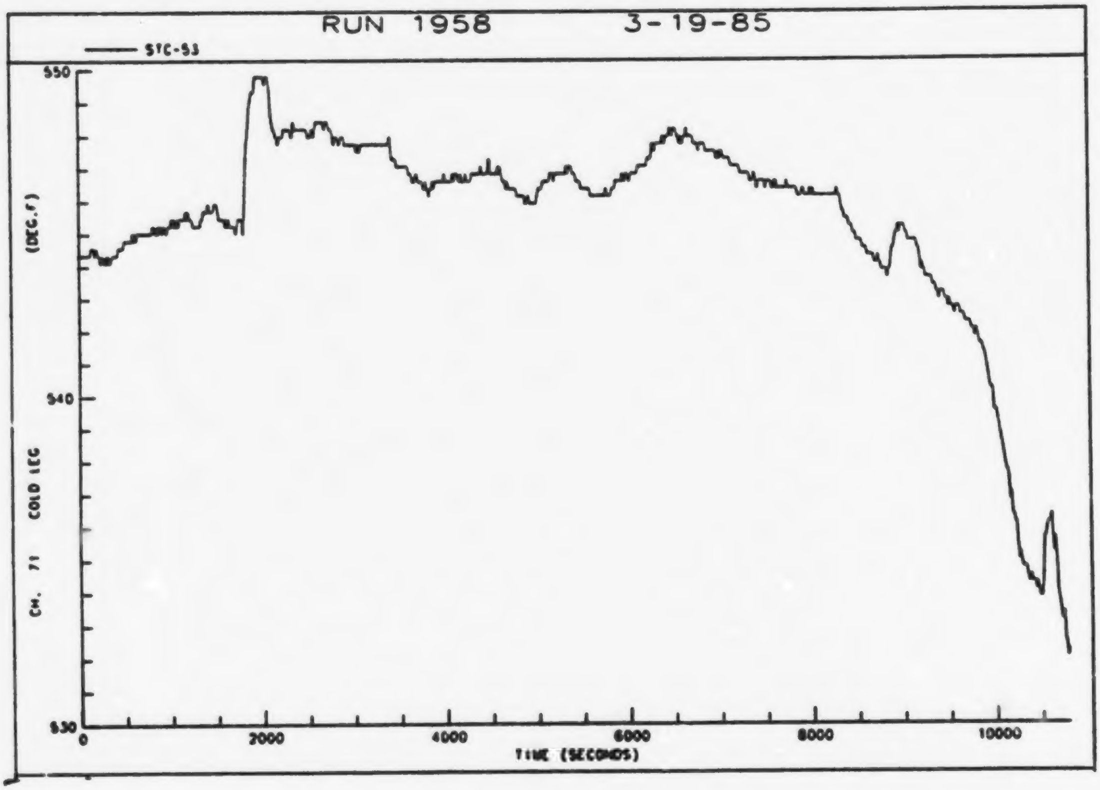

Figure 5-31. Secondary Fluid Temperature (STC-53): Test No. 2 (T-1958)

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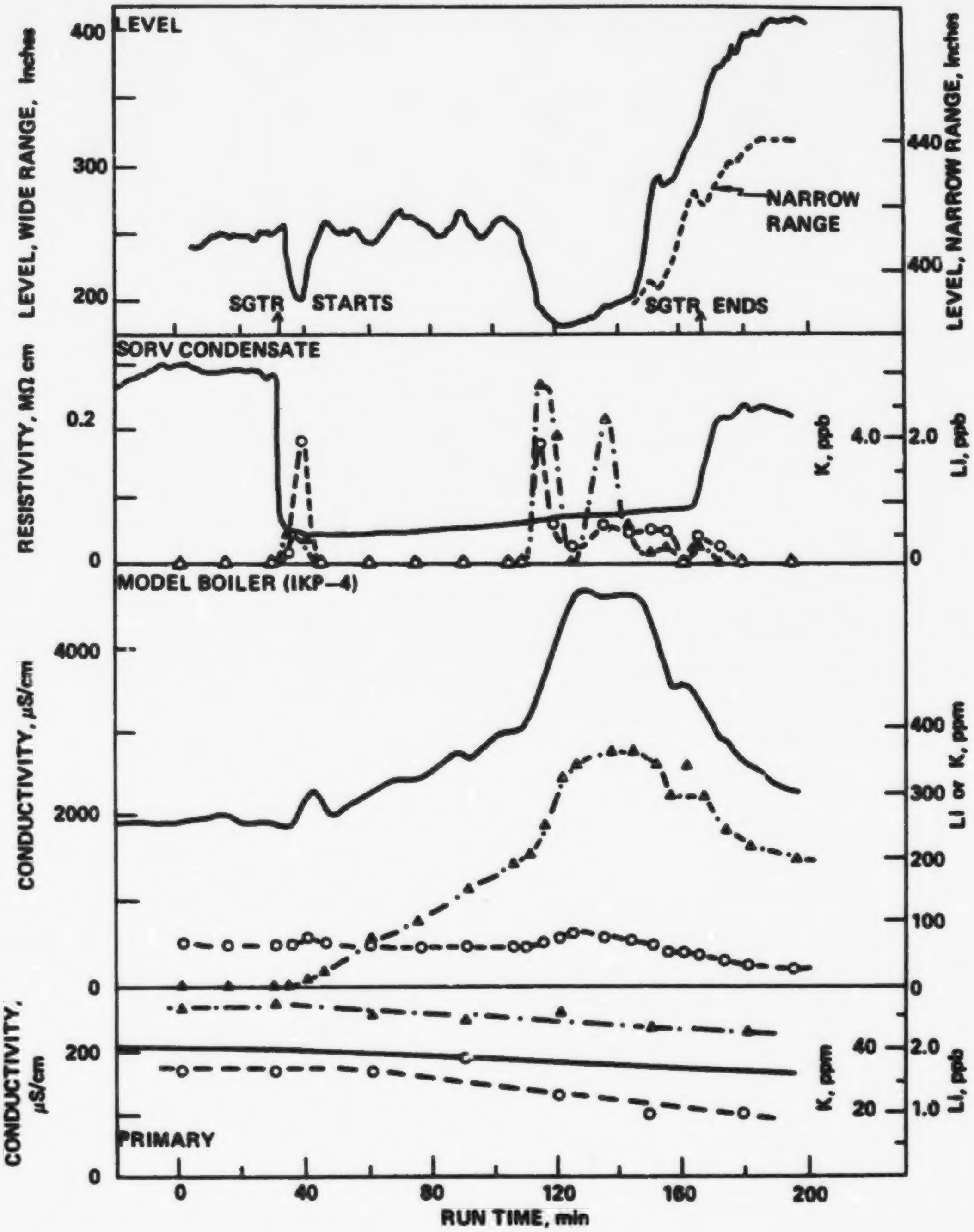

Figure 5-32. Variation in Tracer Concentrations: Test No. 2 (T-1958)

—— LEVEL RESISTIVITY OR CONDUCTIVITY

—○— LITHIUM CONCENTRATION

-·▲·- POTASSIUM CONCENTRATION

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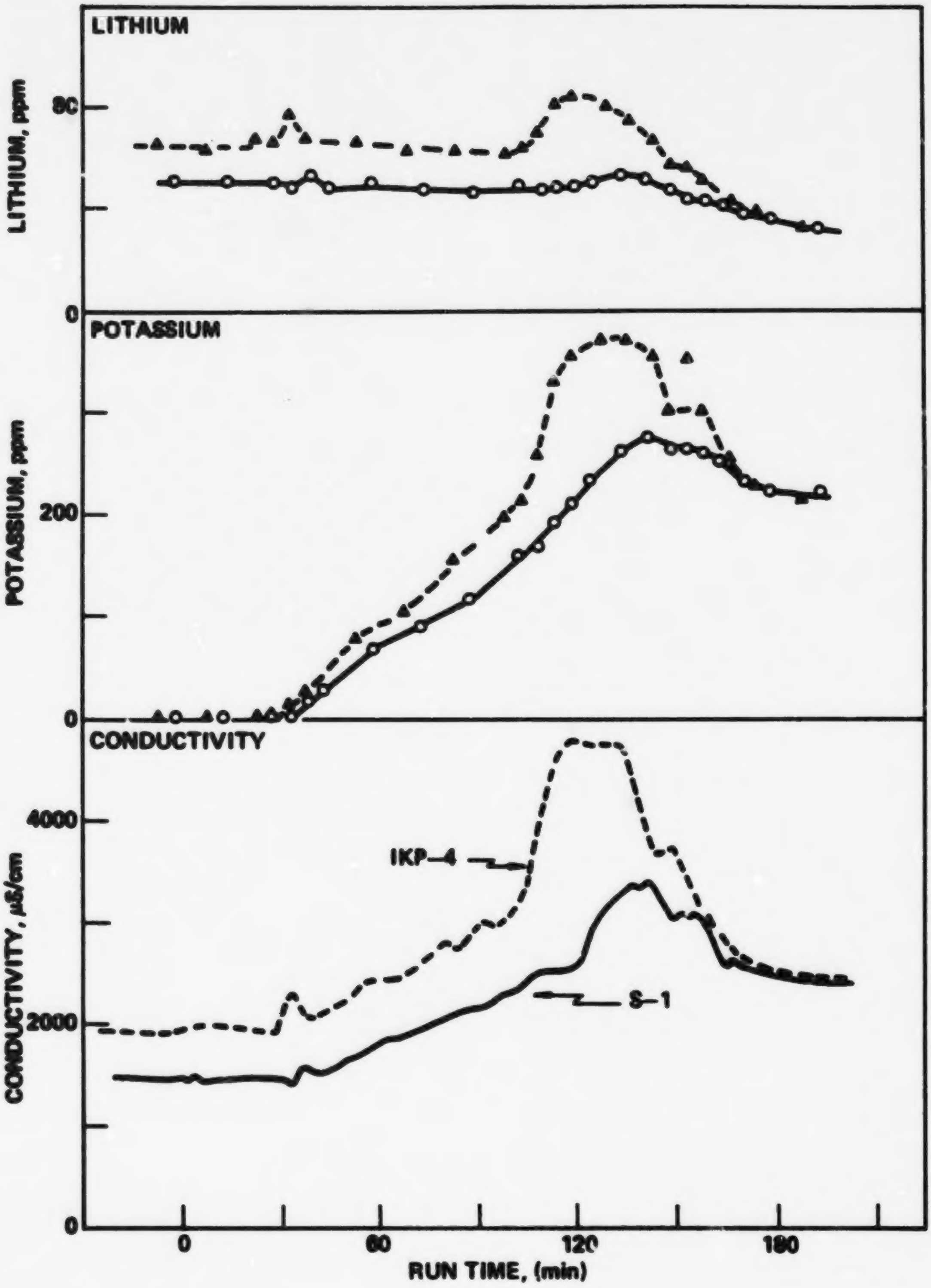

Figure 5-33. Comparison Between S-1 (○) and IKP-4 (▲) Results After Correcting for Sample Line Delays: Test No. 2 (T-1958)

200

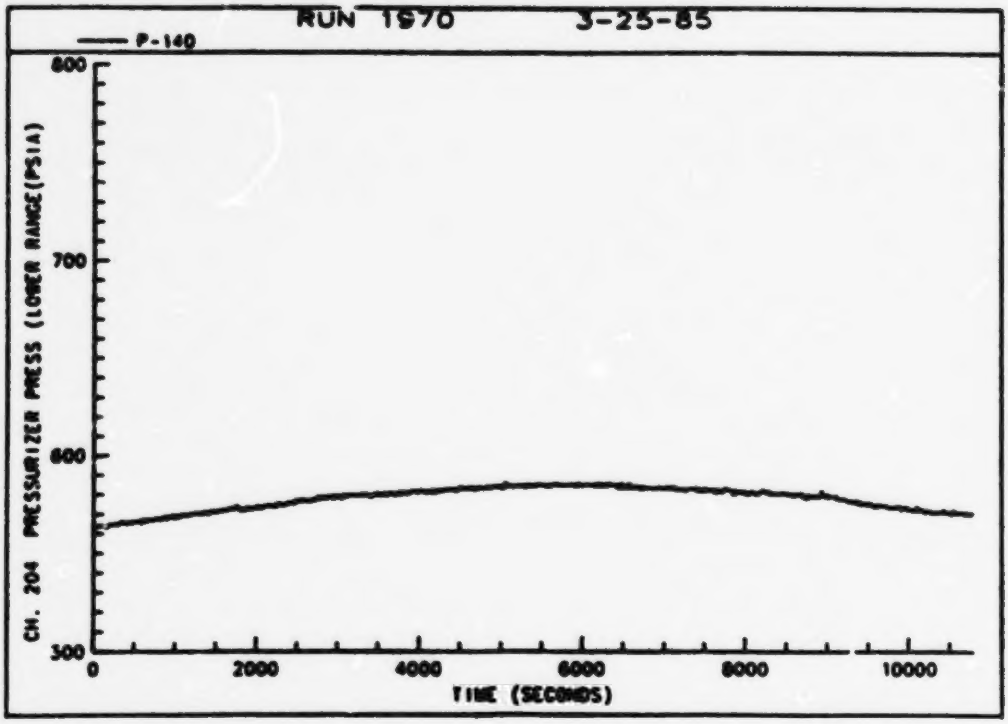

Figure 5-34. Primary System (Pressurizer) Pressure (P-140): Test No. 3 (T-1970)

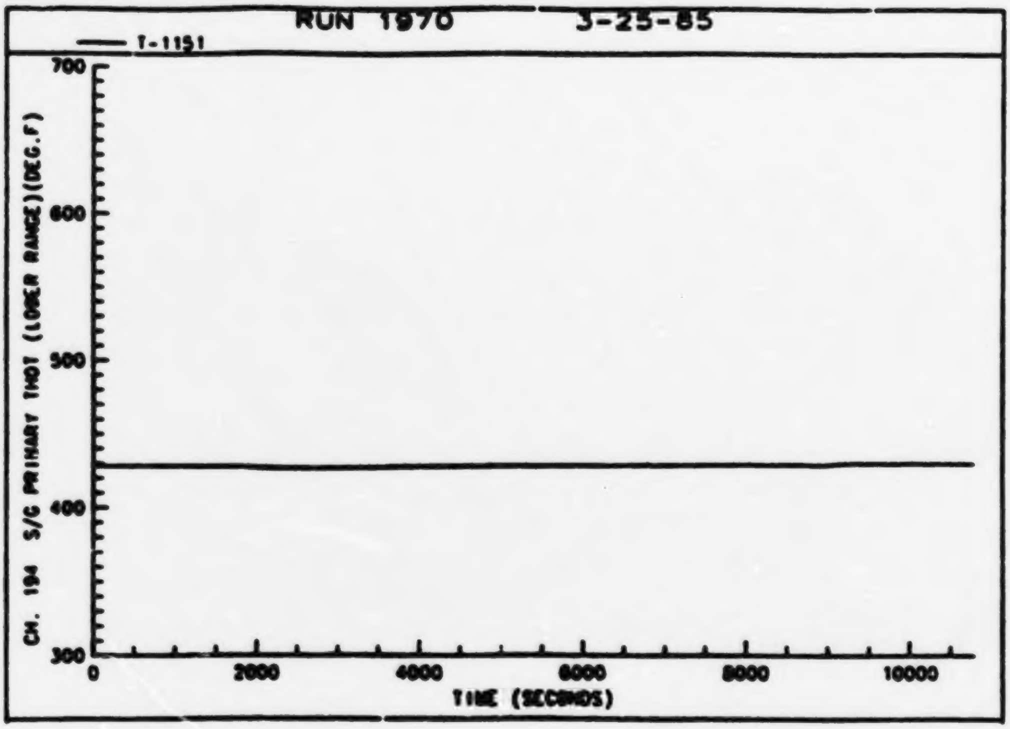

Figure 5-35. Primary Fluid T_{hot} (T-1151): Test No. 3 (T-1970)

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201

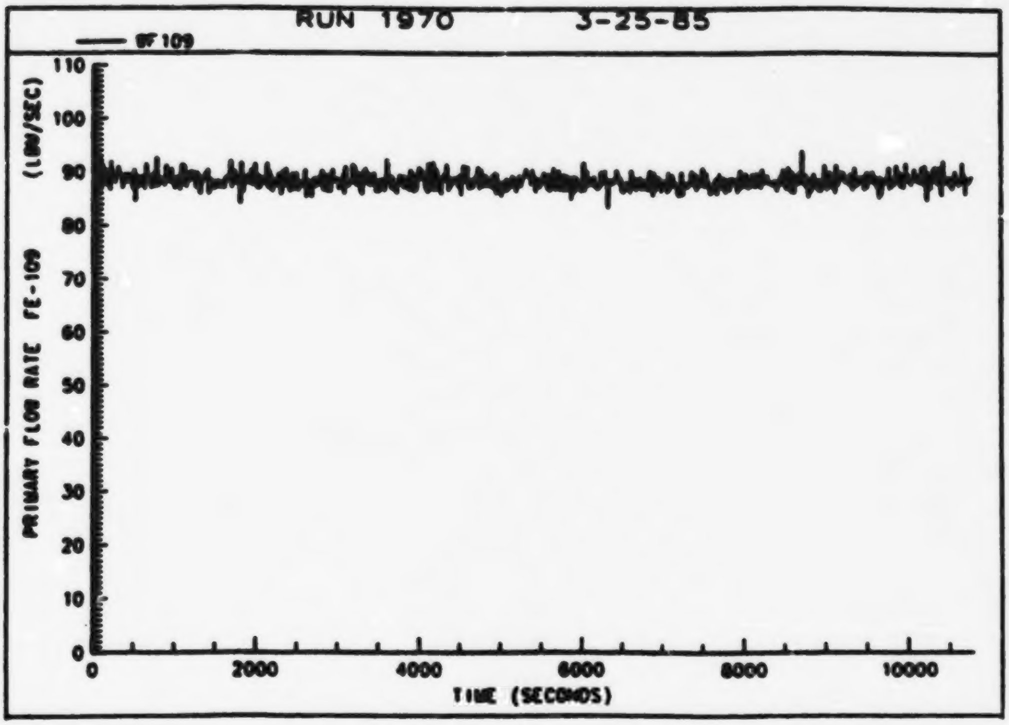

Figure 5-36. Primary Fluid Flow Rate (WF-109): Test No. 3 (T-1970)

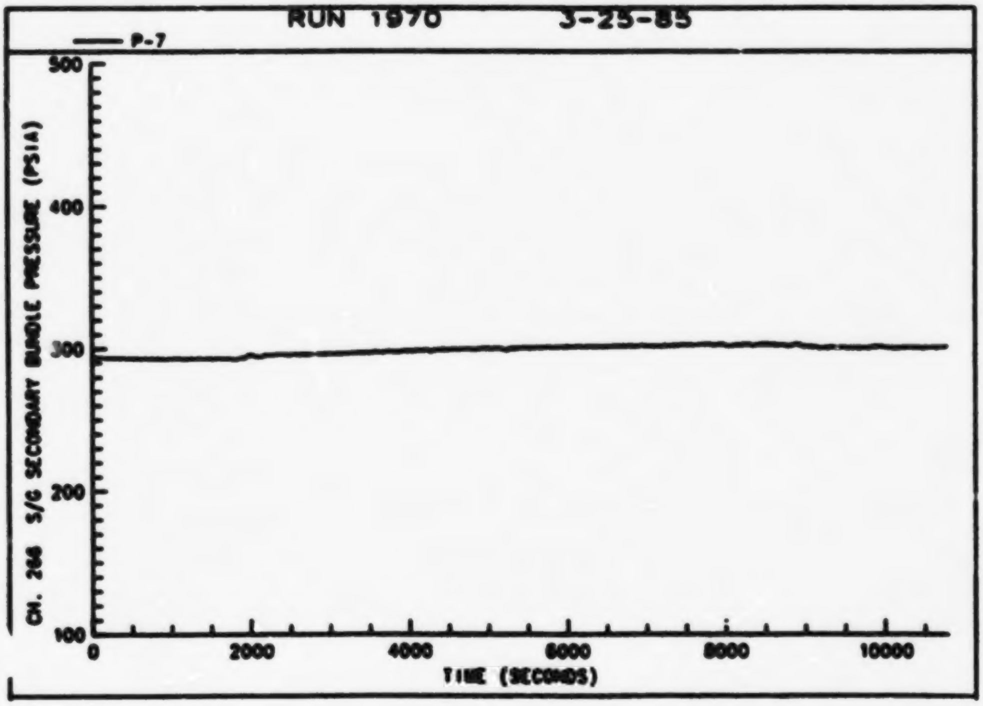

Figure 5-37. Secondary Side Pressure (P-7): Test No. 3 (T-1970)

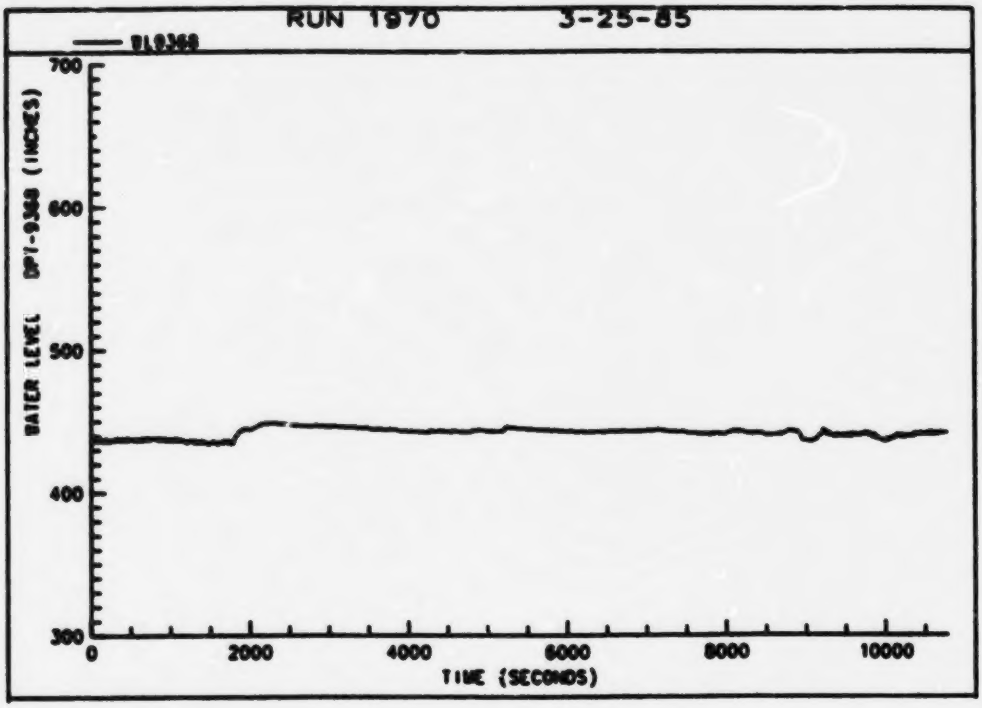

Figure 5-38. Downcomer Water Level - Narrow Range (WL-9368): Test No. 3 (T-1970)

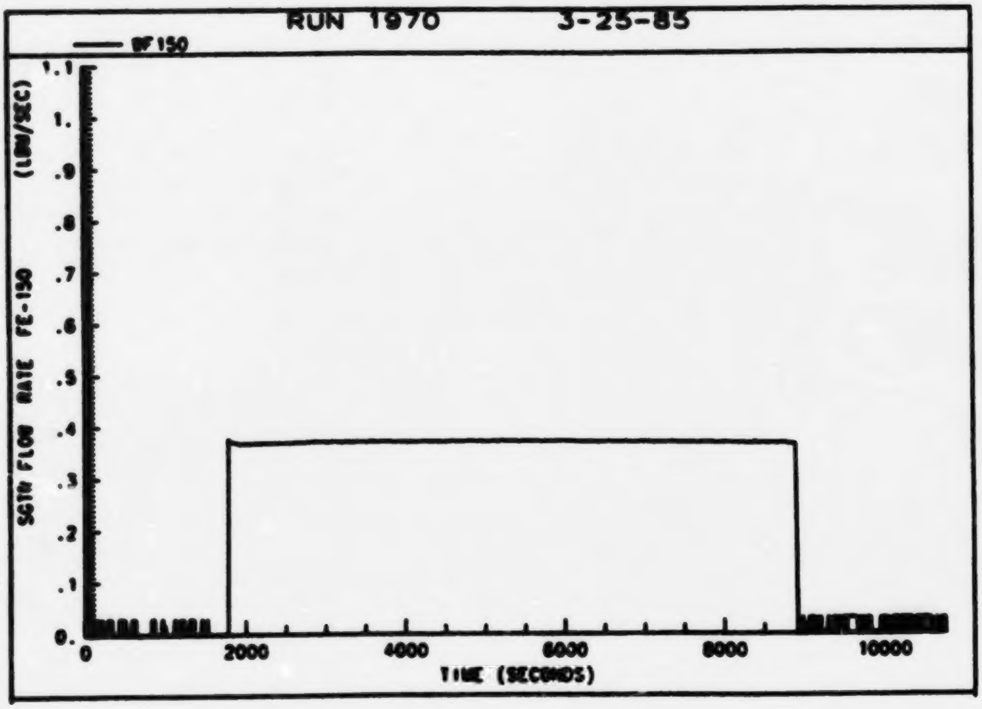

Figure 5-39. SGTR Flow Rate (WF-150): Test No. 3 (T-1970)

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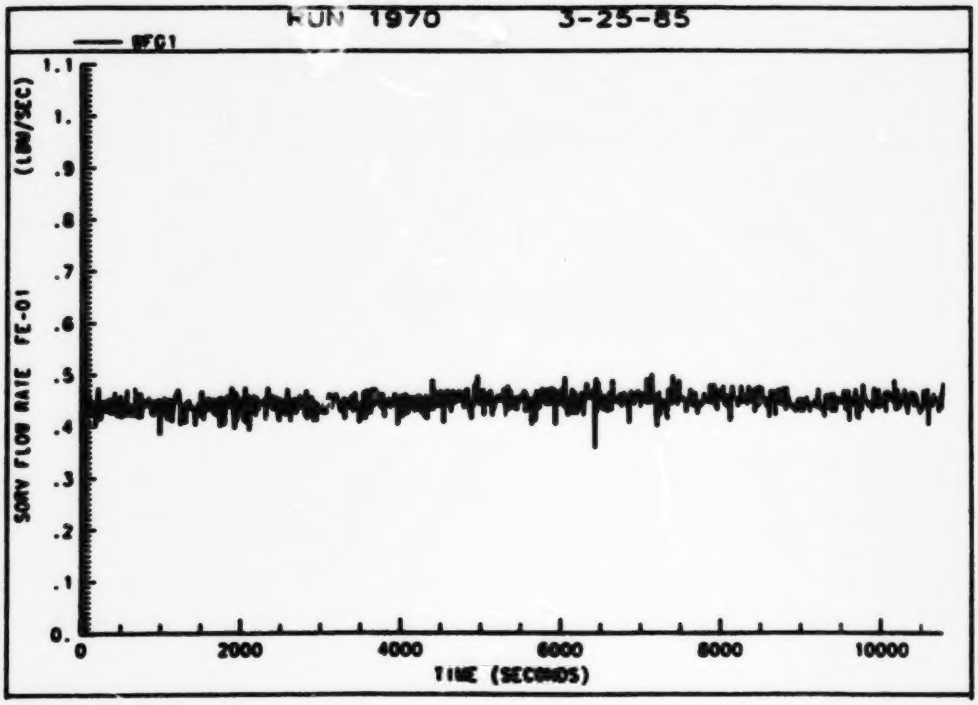

Figure 5-40. SORV Flow Rate (WF-01): Test No. 3 (T-1970)

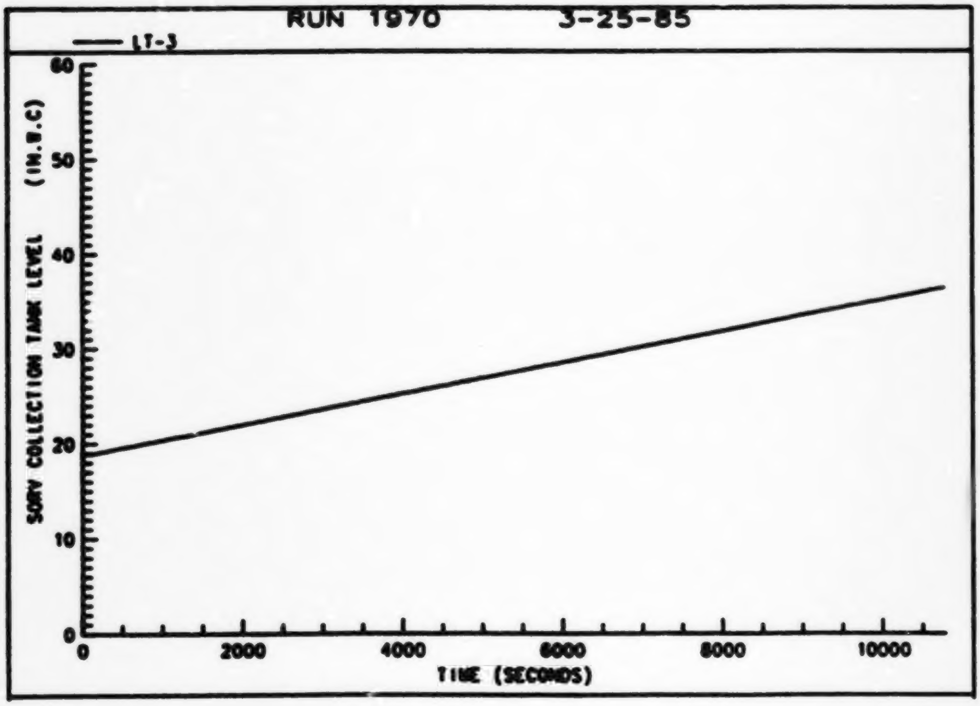

Figure 5-41. SORV Tank Level (LT-3): Test No. 3 (T-1970)

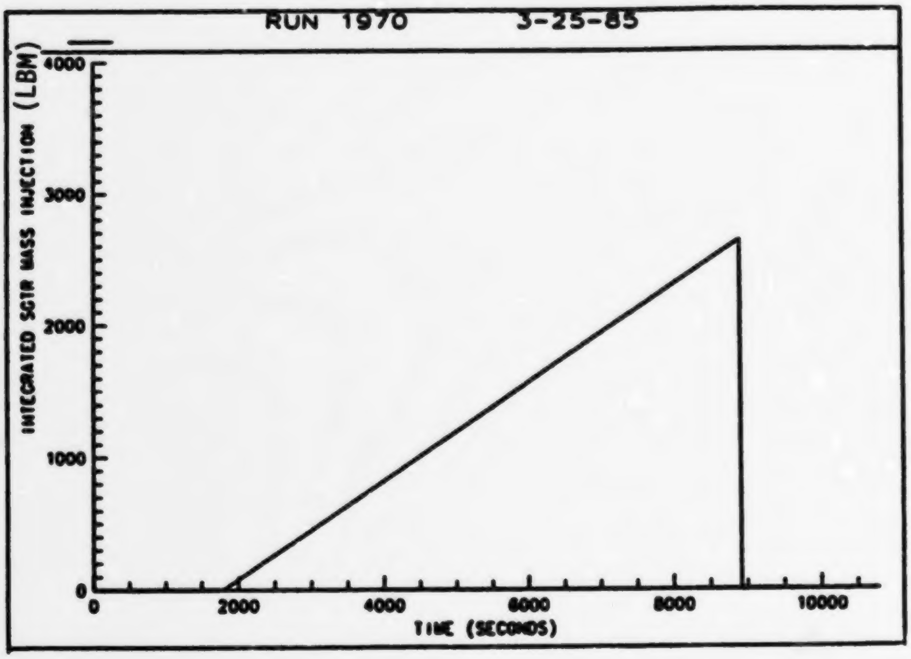

Figure 5-42. Integrated SGTR Flow: Test No. 3 (T-1970)

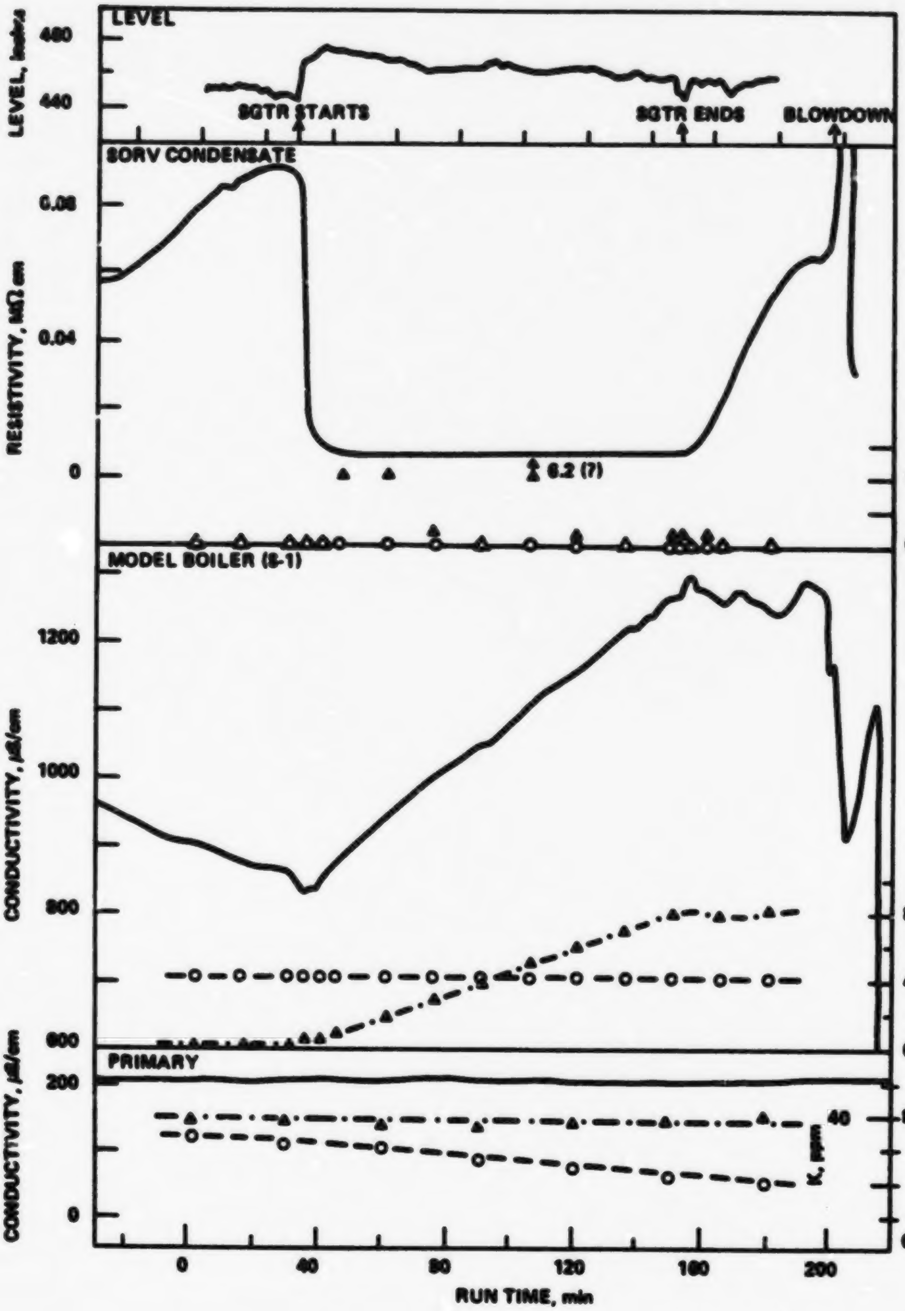

Figure 5-43. Variation in Tracer Concentrations: Test No. 3 (T-1970)

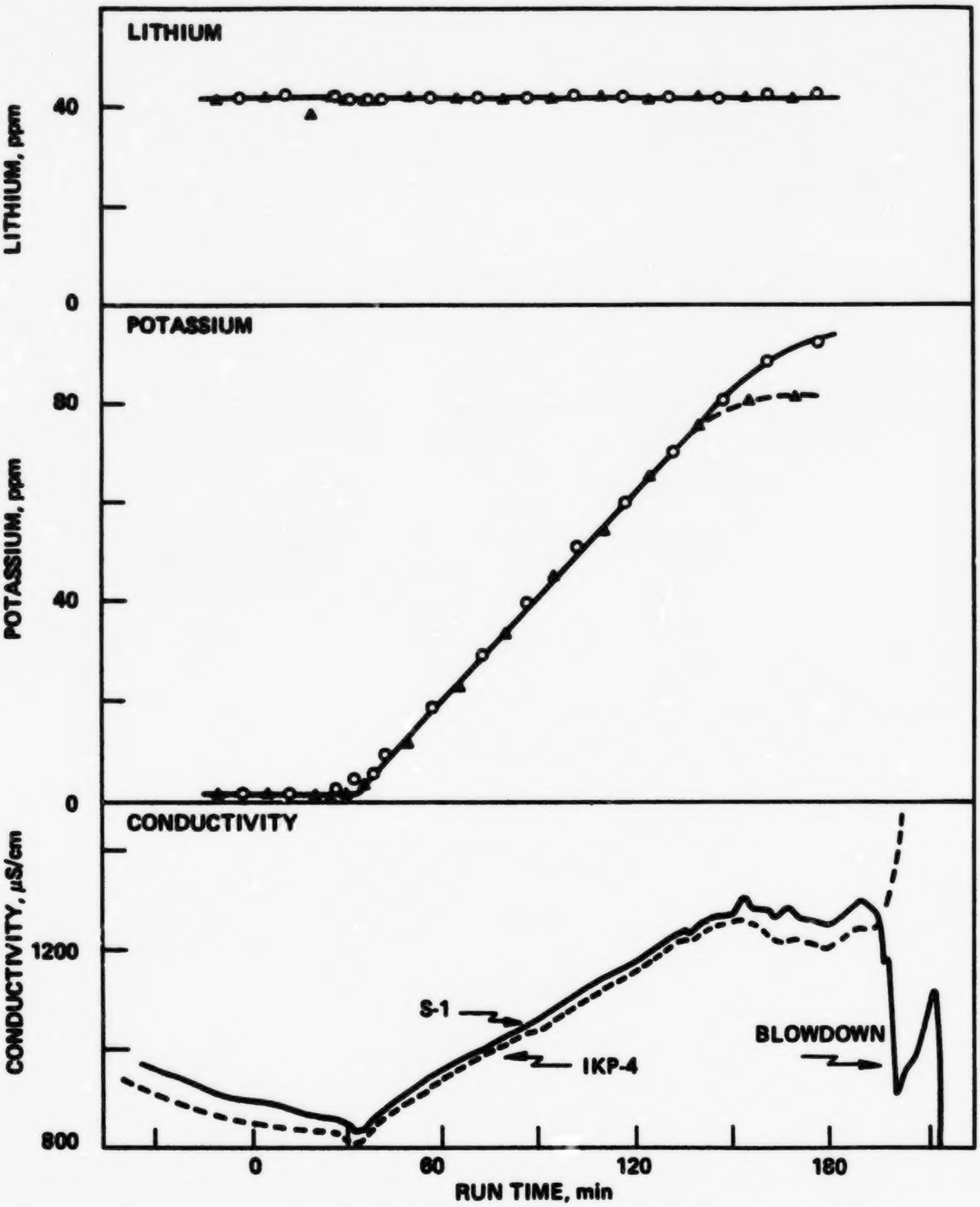

Figure 5-44. Comparison Between S-1 (○) and IKP-4 (▲) Results After Correcting for Sample Line Delays: Test No. 3 (T-1970)

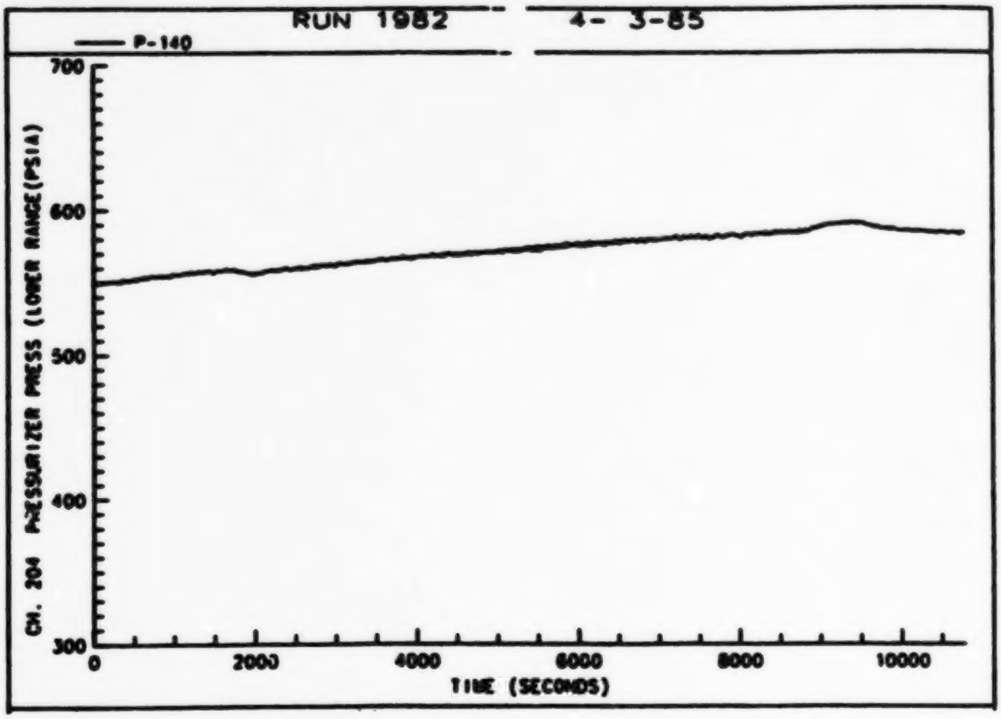

Figure 5-45. Primary System (Pressurizer) Pressure (P-140): Test No. 4 (T-1982)

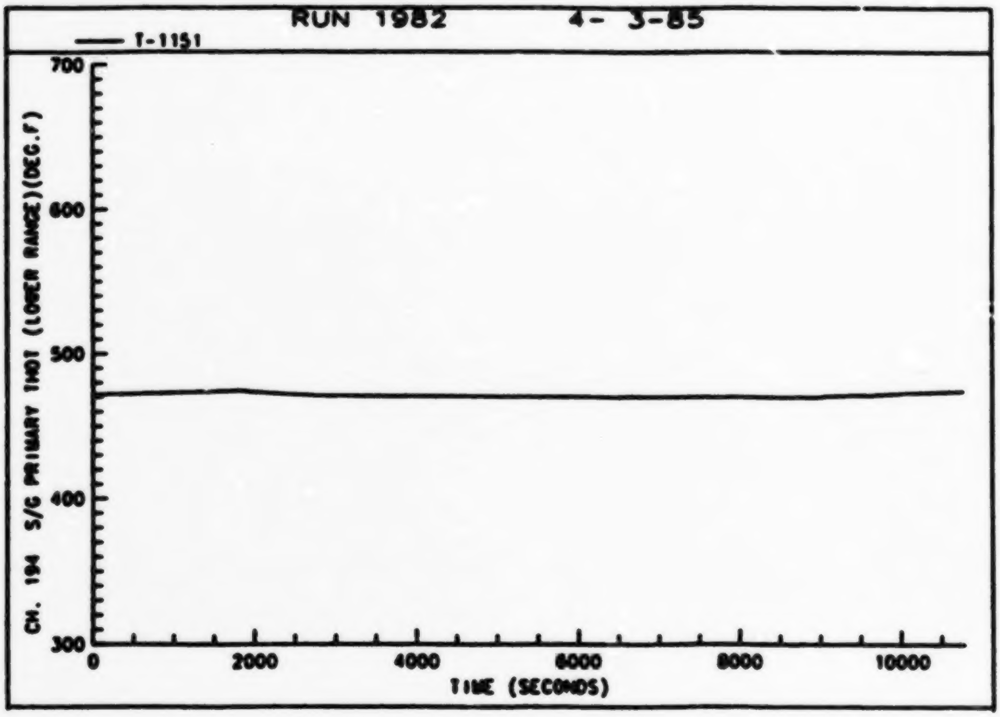

Figure 5-46. Primary Fluid T_{hot} (T-1151): Test No. 4 (T-1982)

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208

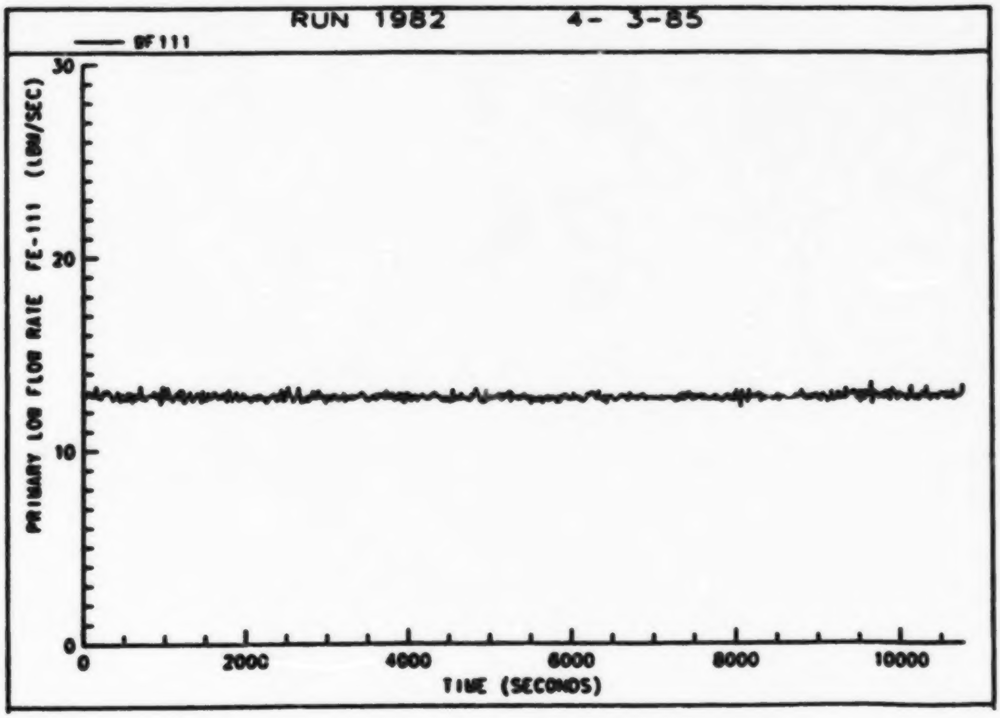

Figure 5-47. Primary Fluid Flow Rate (WF-111): Test No. 4 (T-1982)

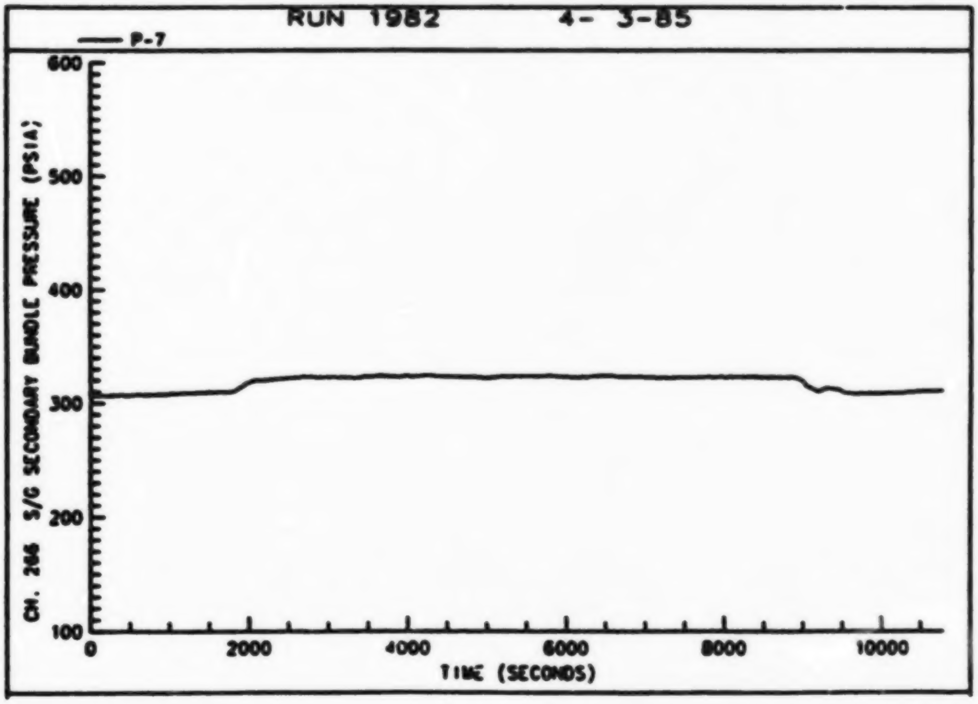

Figure 5-48. Secondary Side Pressure (P-7): Test No. 4 (T-1982)

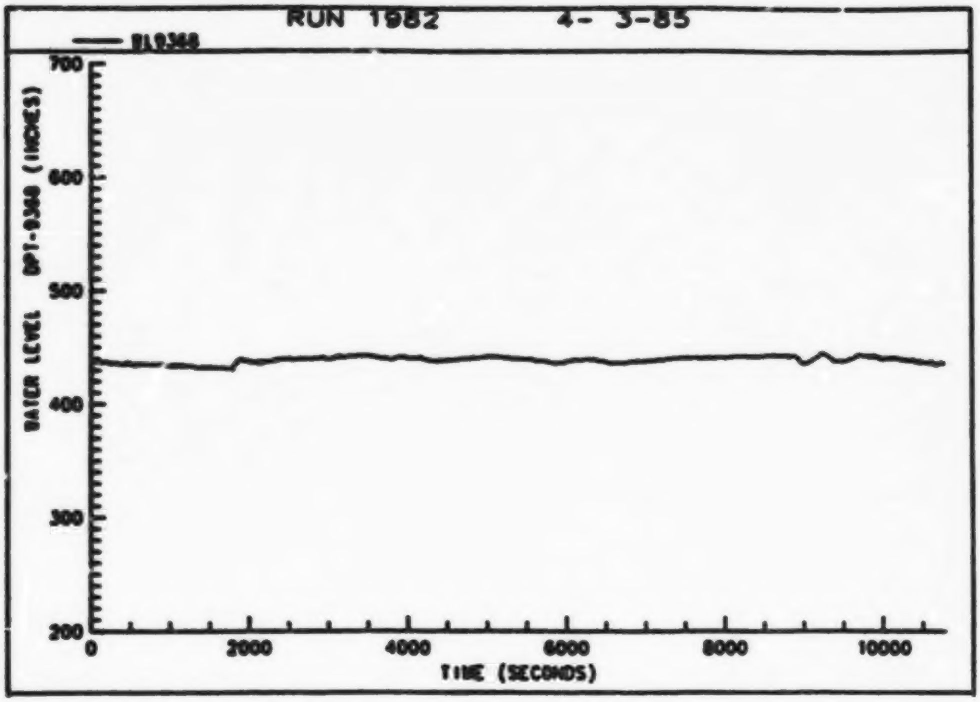

Figure 5-49. Downcomer Water Level - Narrow Range (WL-9368): Test No. 4 (T-1982)

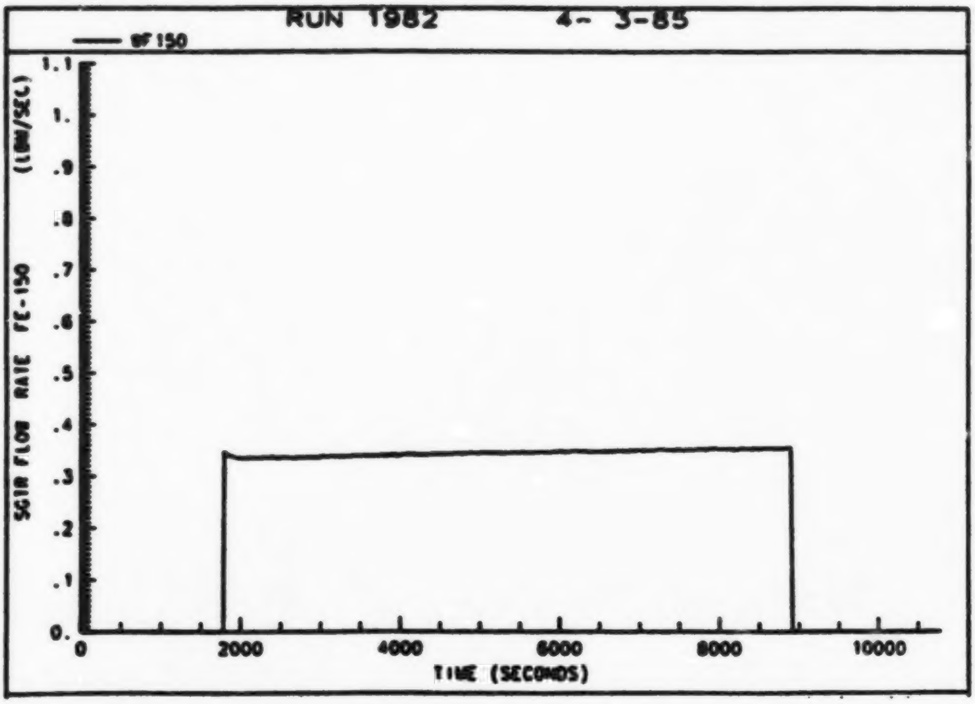

Figure 5-50. SGTR Flow Rate (WF-150): Test No. 4 (T-1982)

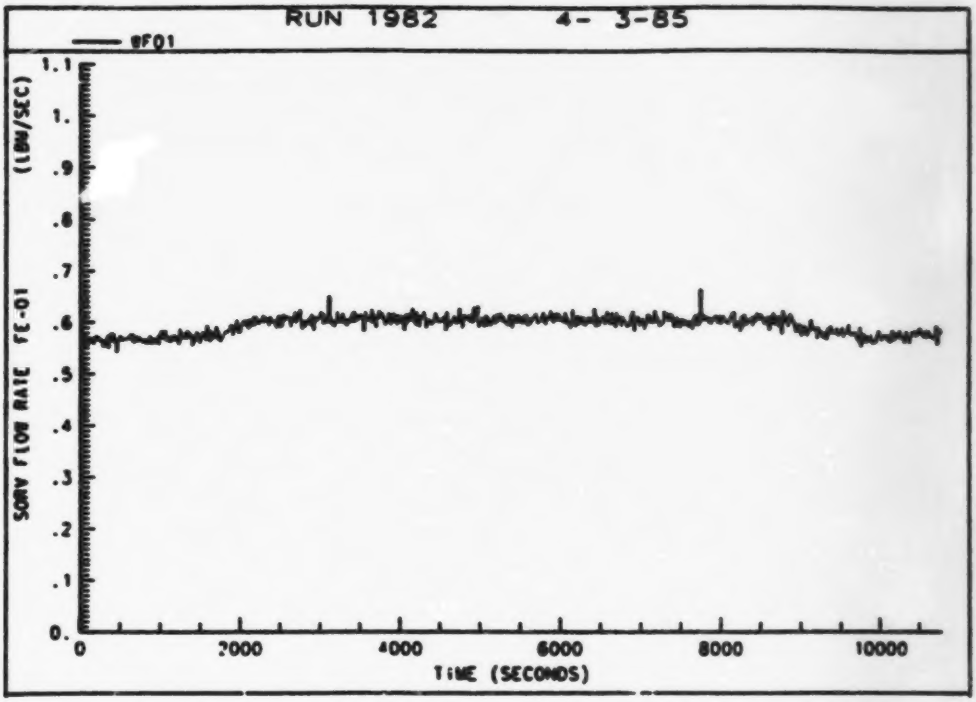

Figure 5-51. SORV Flow Rate (WF-01): Test No. 4 (T-1982)

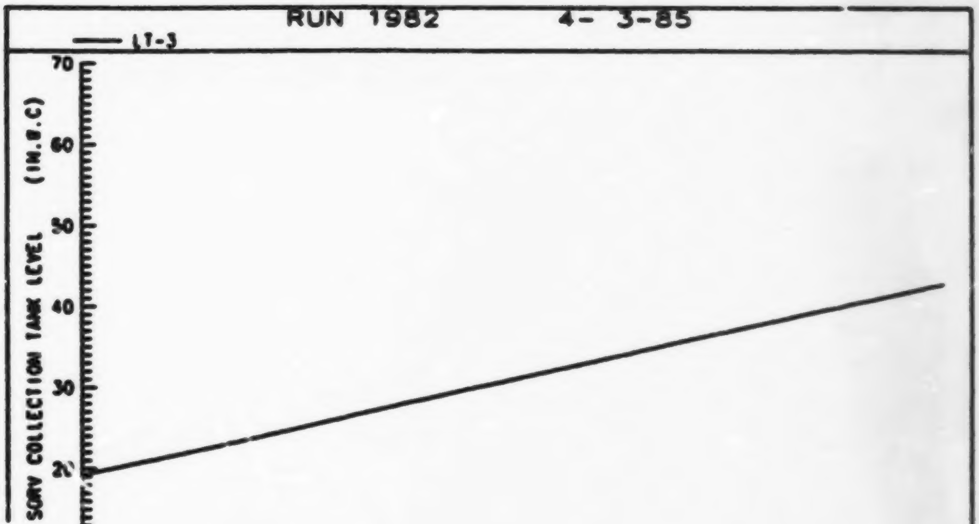

Figure 5-52. SORV Tank Level (LT-3): Test No. 4 (T-1982)

211

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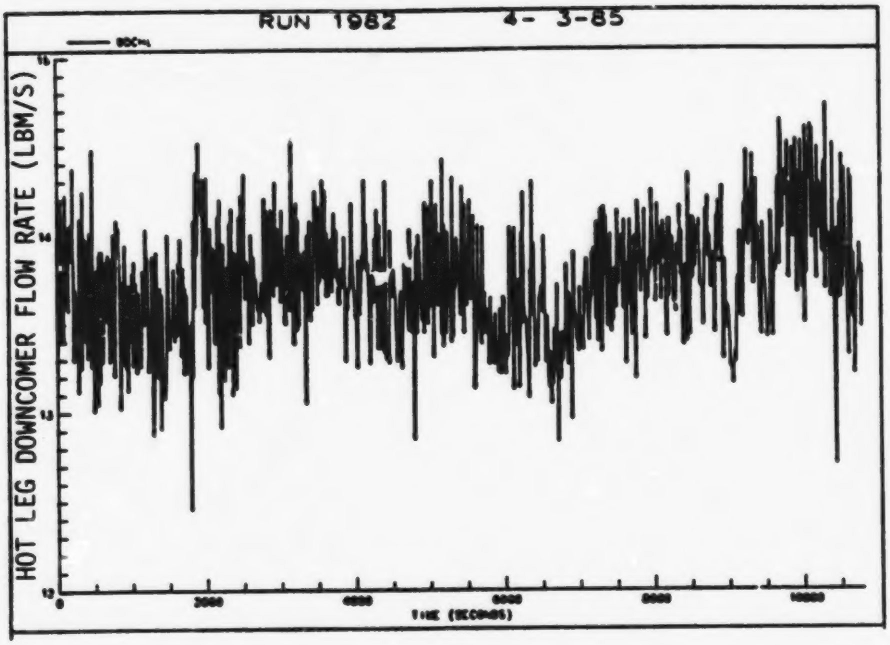

Figure 5-53. Hot Leg Downcomer Flow Rate (WDCHL): Test No. 4 (T-1982)

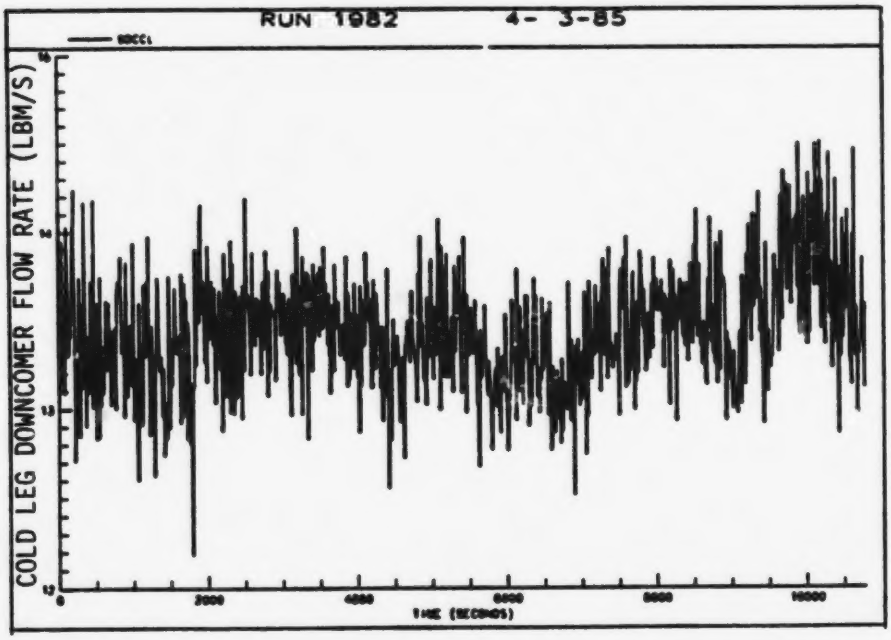

Figure 5-54. Cold Leg Downcomer Flow Rate (WDCCL): Test No. 4 (T-1982)

212

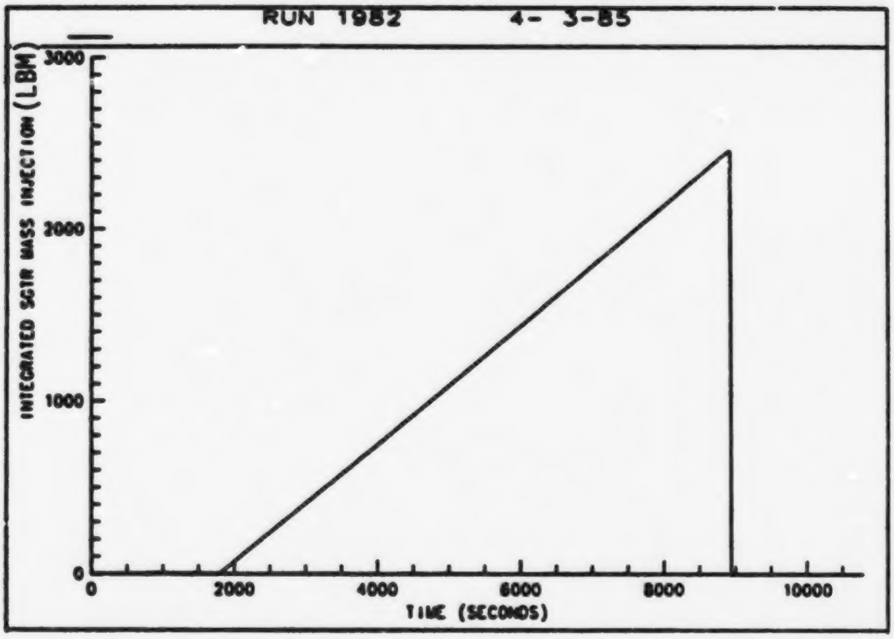

Figure 5-55. Integrated SGTR Flow: Test No. 4 (T-1982)

213

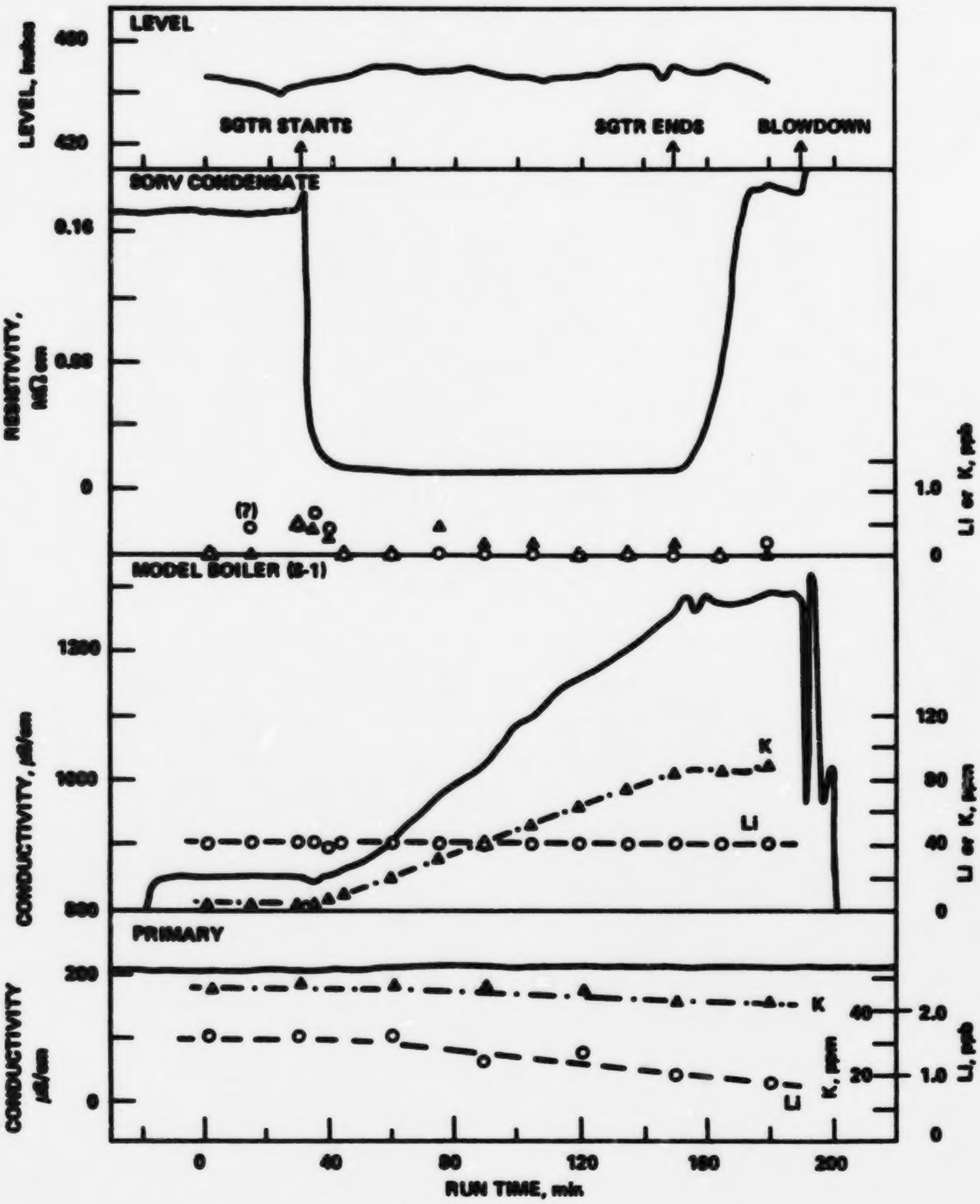

Figure 5-56. Variation in Tracer Concentrations:
Test No. 4 (T-1982)

—— LEVEL, RESISTIVITY OR CONDUCTIVITY

—○— LITHIUM CONCENTRATION

—·△—· POTASSIUM CONCENTRATION

214

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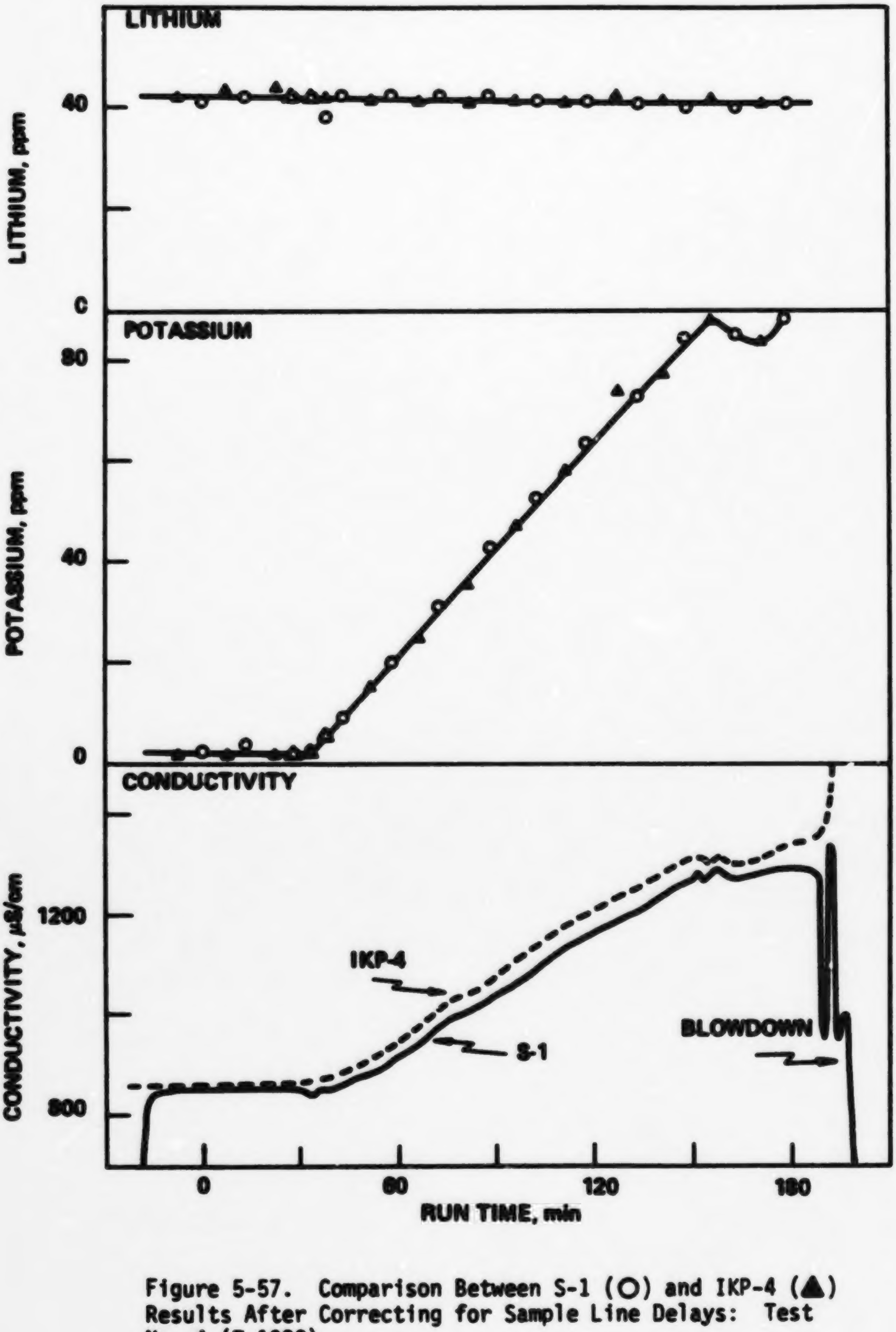

Figure 5-57. Comparison Between S-1 (○) and IKP-4 (▲) Results After Correcting for Sample Line Delays: Test No. 4 (T-1982)

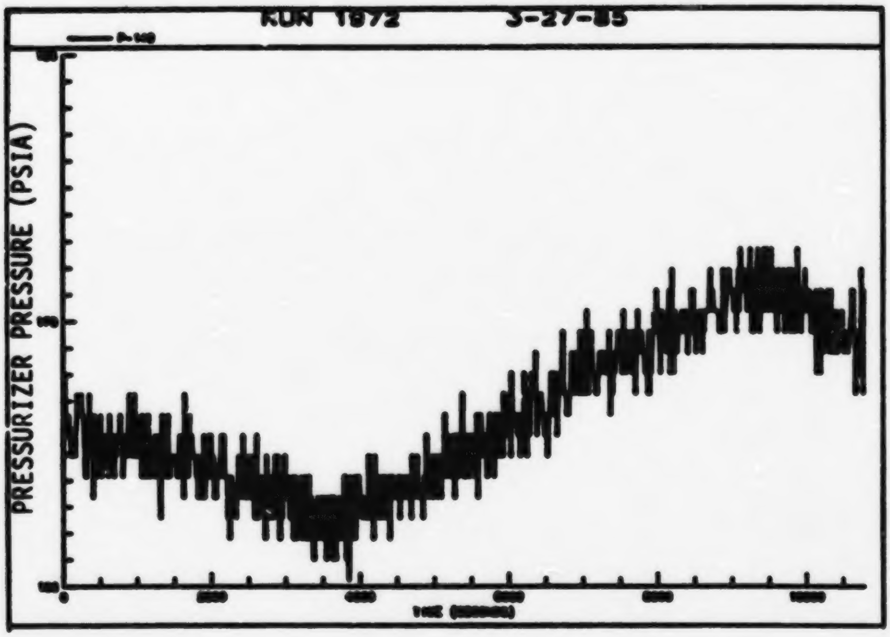

Figure 5-58. Primary System (Pressurizer) Pressure (P-140): Test No. 5 (T-1972)

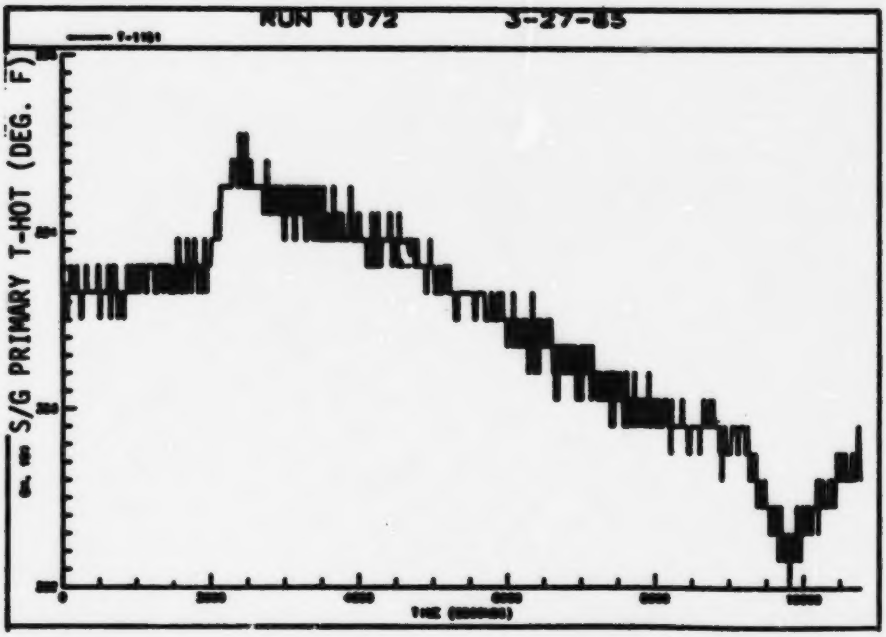

Figure 5-59. Primary Fluid T_{hot} (T-1151): Test No. 5 (T-1972)

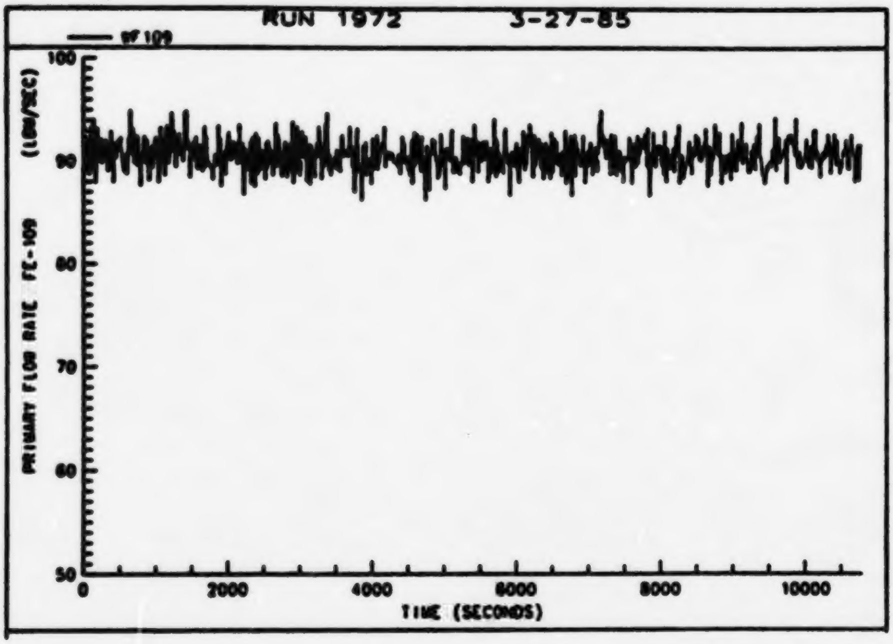

Figure 5-60. Primary Fluid Flow Rate (WF-109): Test No. 5 (T-1972)

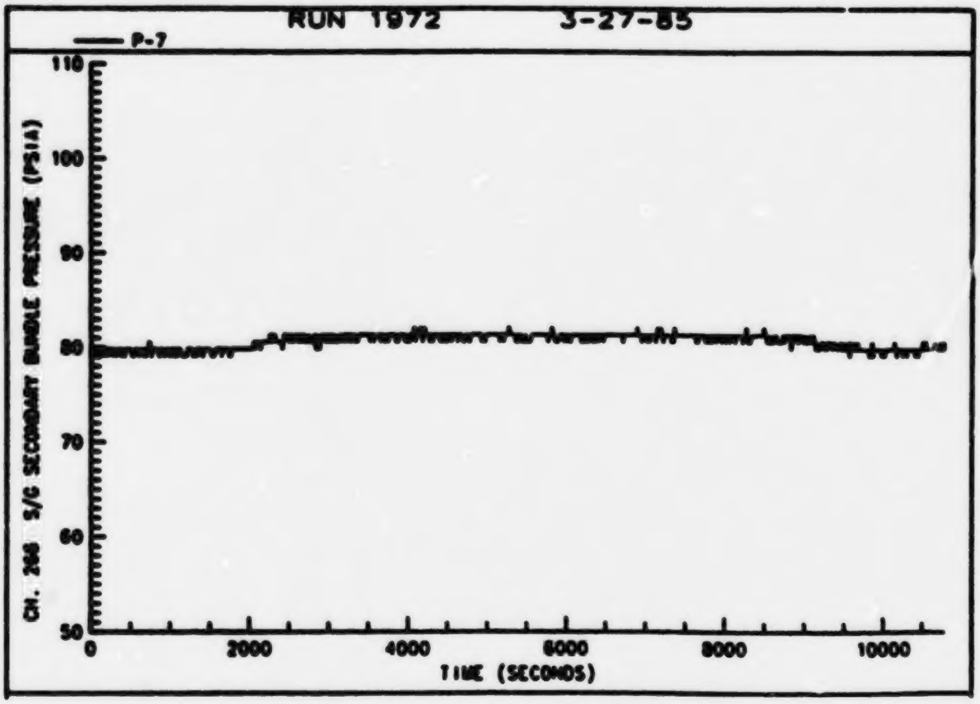

Figure 5-61. Secondary Side Pressure (P-7): Test No. 5 (T-1972)

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217

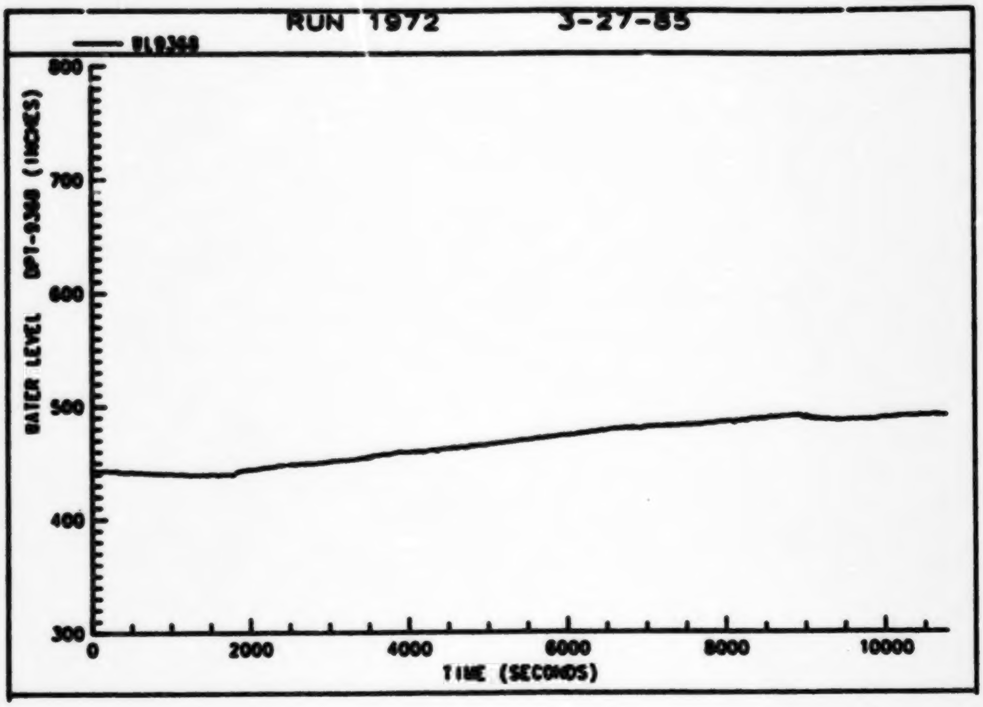

Figure 5-62. Downcomer Water Level - Narrow Range (WL-9368): Test No. 5 (T-1972)

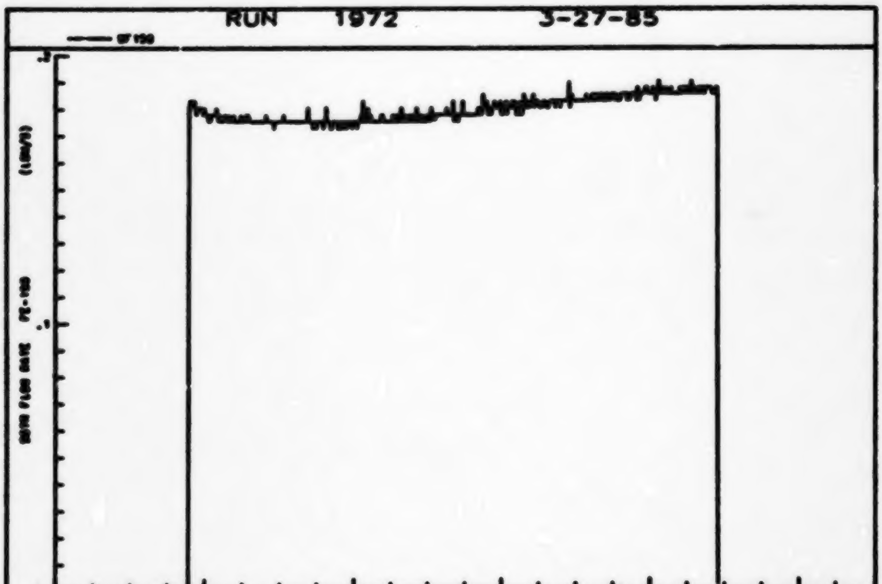

Figure 5-63. SGTR Flow Rate (WF-150): Test No. 5 (T-1976)

218

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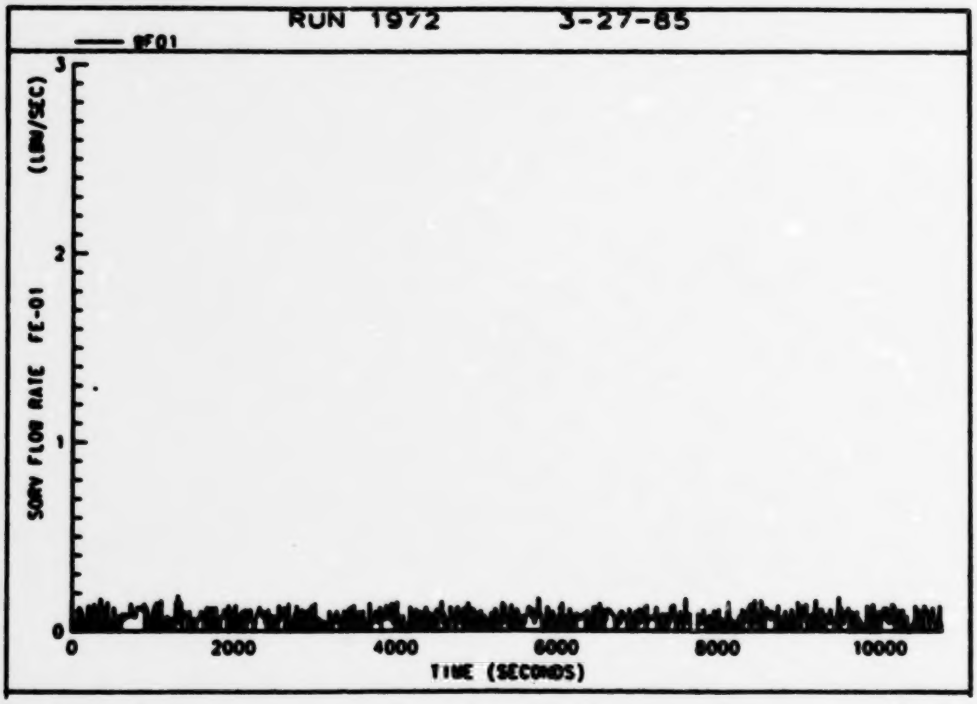

Figure 5-64. SORV Flow Rate (WF-01): Test No. 5 (T-1972)

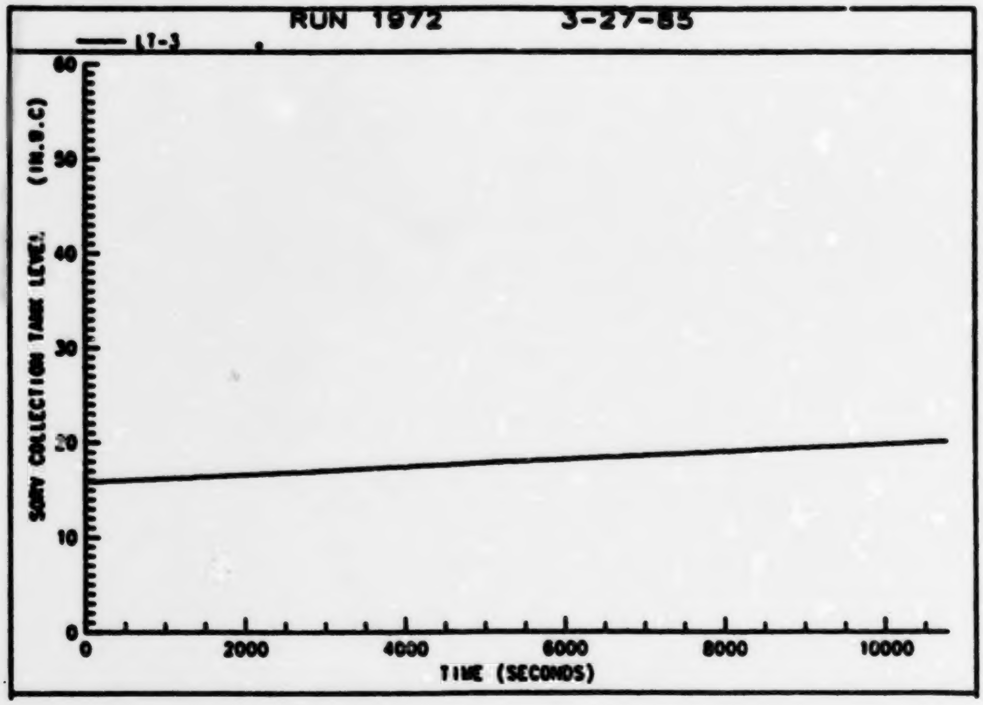

Figure 5-65. SORV Tank Level (LT-3): Test No. 5 (T-1972)

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219

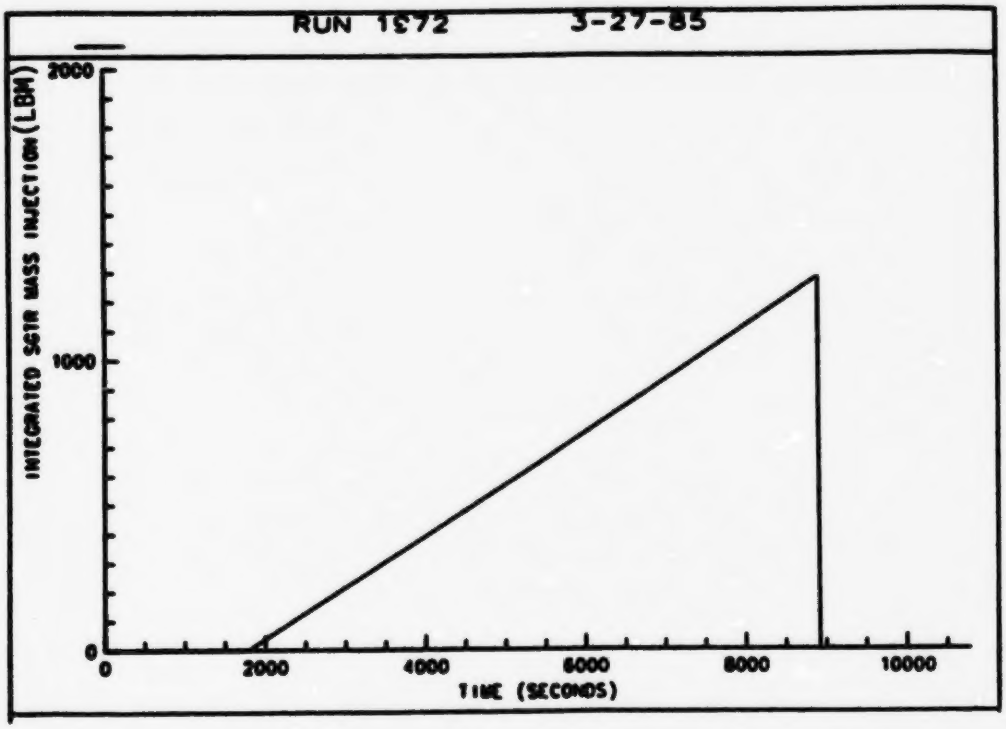

Figure 5-66. Integrated SGTR Flow: Test No. 5 (T-1972)

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220

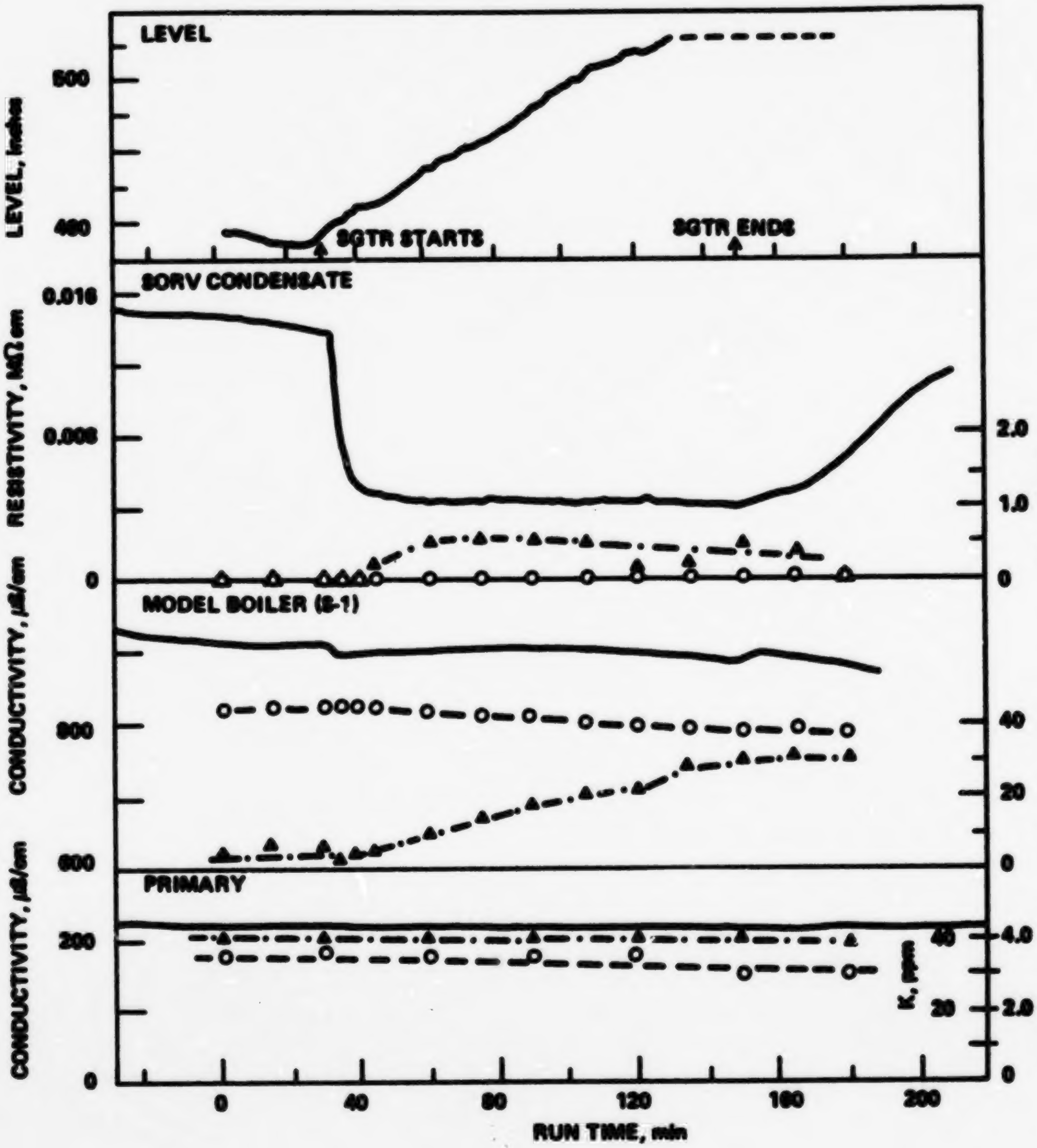

Figure 5-67. Variation in Tracer Concentrations: Test No. 5 (T-1972) (N.B. Uncorrected Water Level Plotted)

—— LEVEL, RESISTIVITY OR CONDUCTIVITY

—○— LITHIUM CONCENTRATION

–·△–· POTASSIUM CONCENTRATION

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221

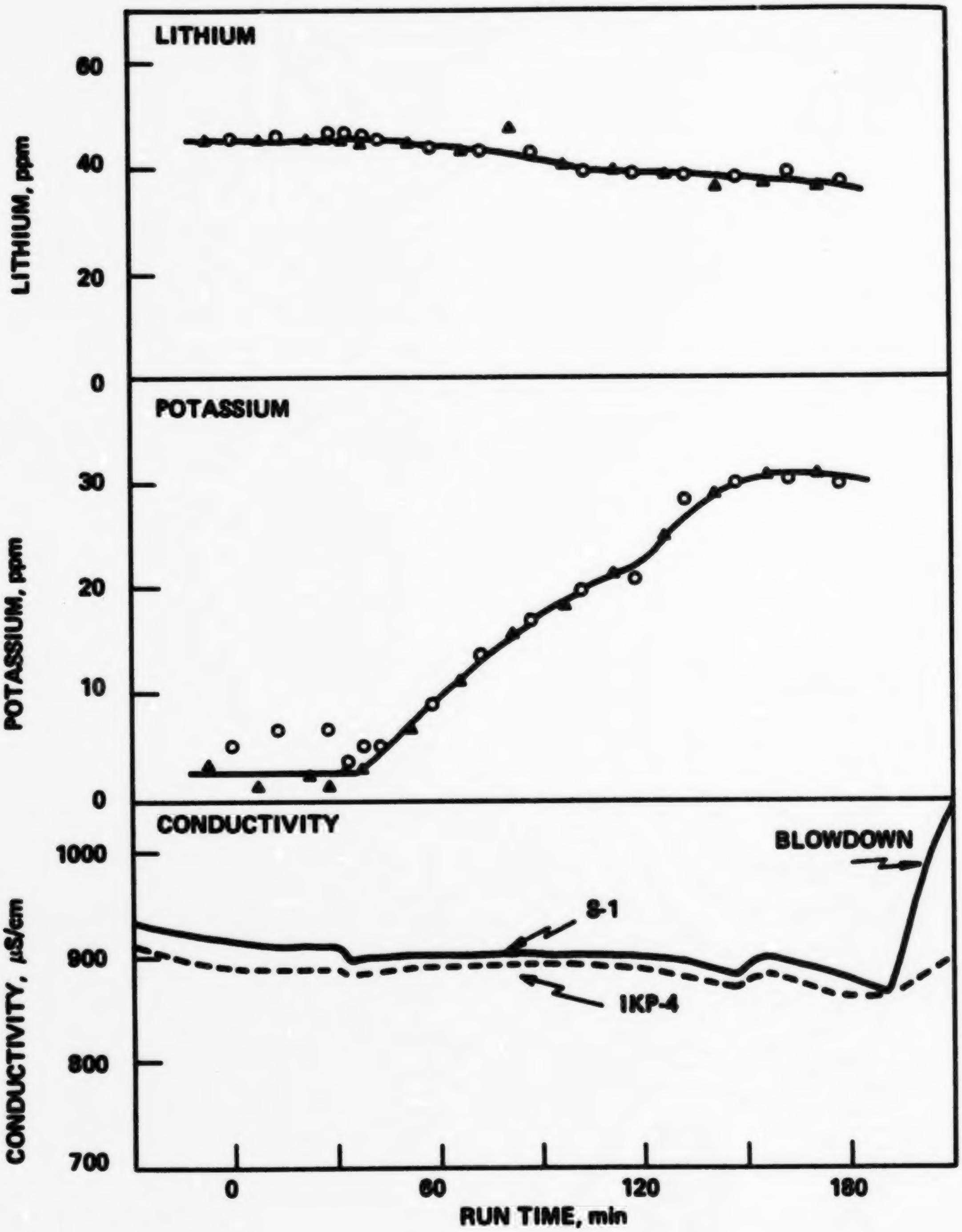

Figure 5-68. Comparison Between S-1 (○) and IKP-4 (▲) Results After Correcting for Sample Line Delays: Test No. 5 (T-1972)

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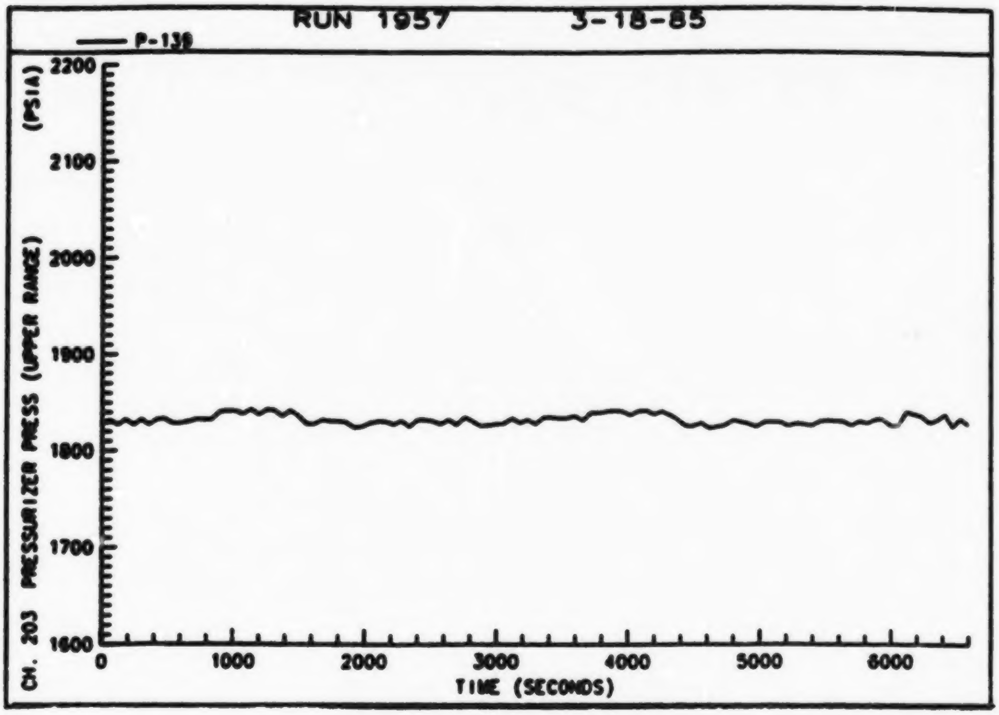

Figure 5-69. Primary System (Pressurizer) Pressure (P-139): Test No. 6 (T-1957)

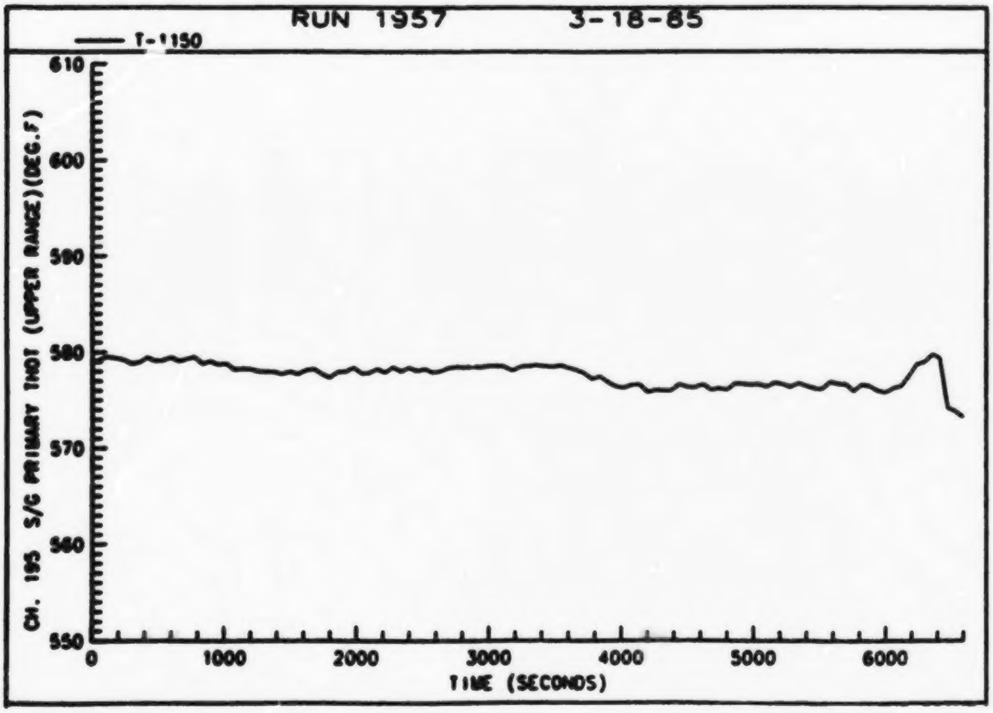

Figure 5-70. Primary Fluid T_{hot} (T-1150): Test No. 6 (T-1957)

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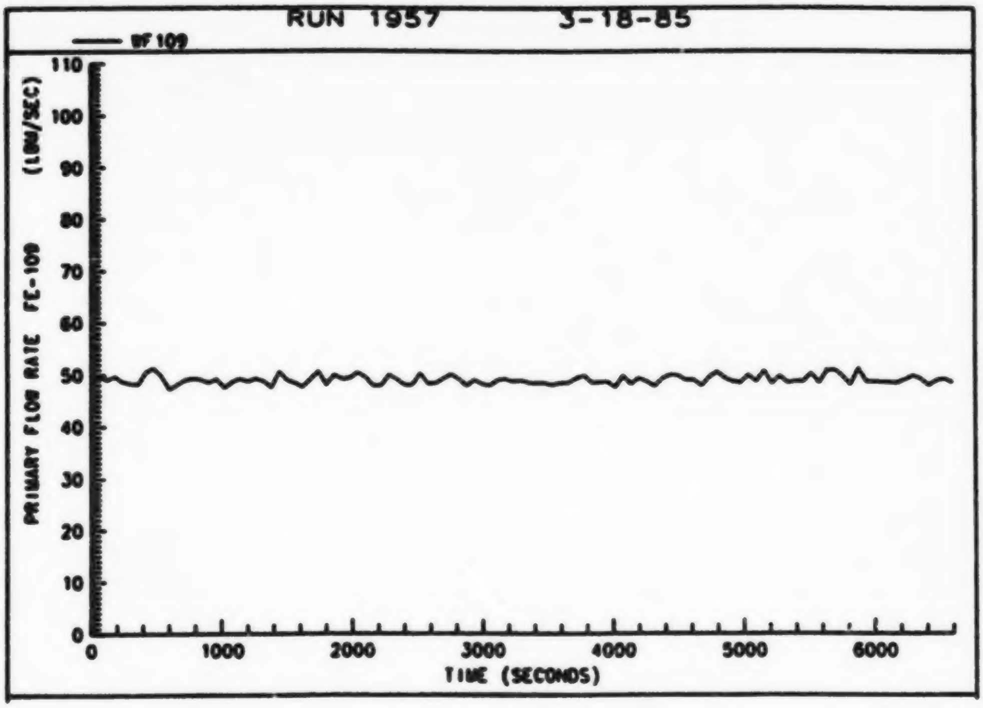

Figure 5-71. Primary Fluid Flow Rate (WF-109): Test No. 6 (T-1957)

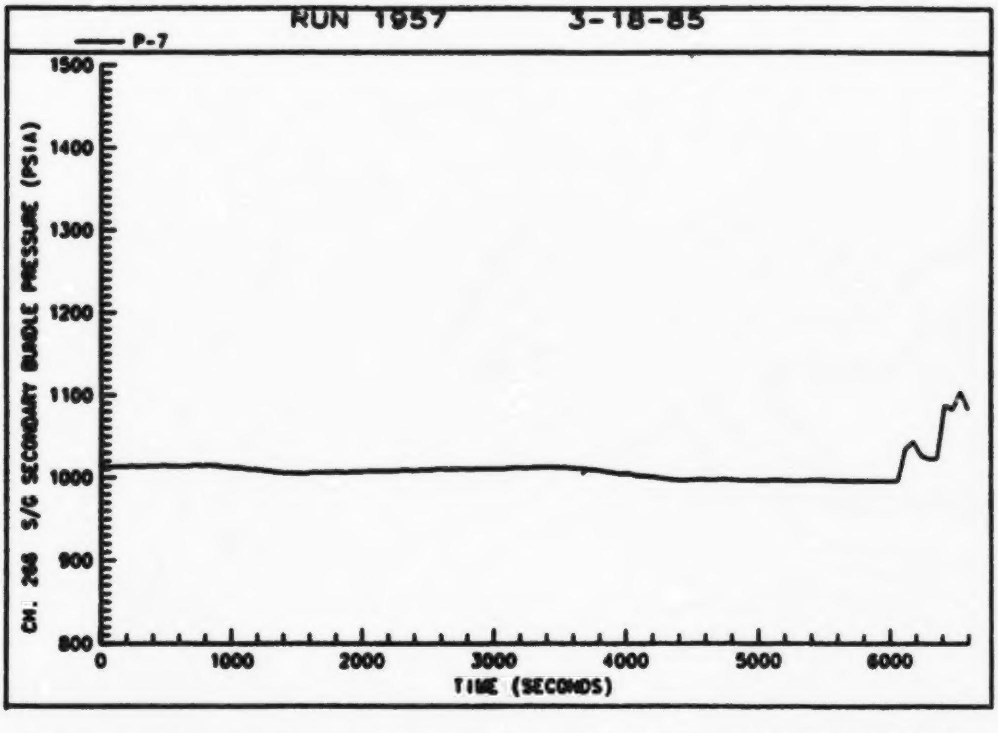

Figure 5-72. Secondary Side Pressure (P-7): Test No. 6 (T-1957)

224

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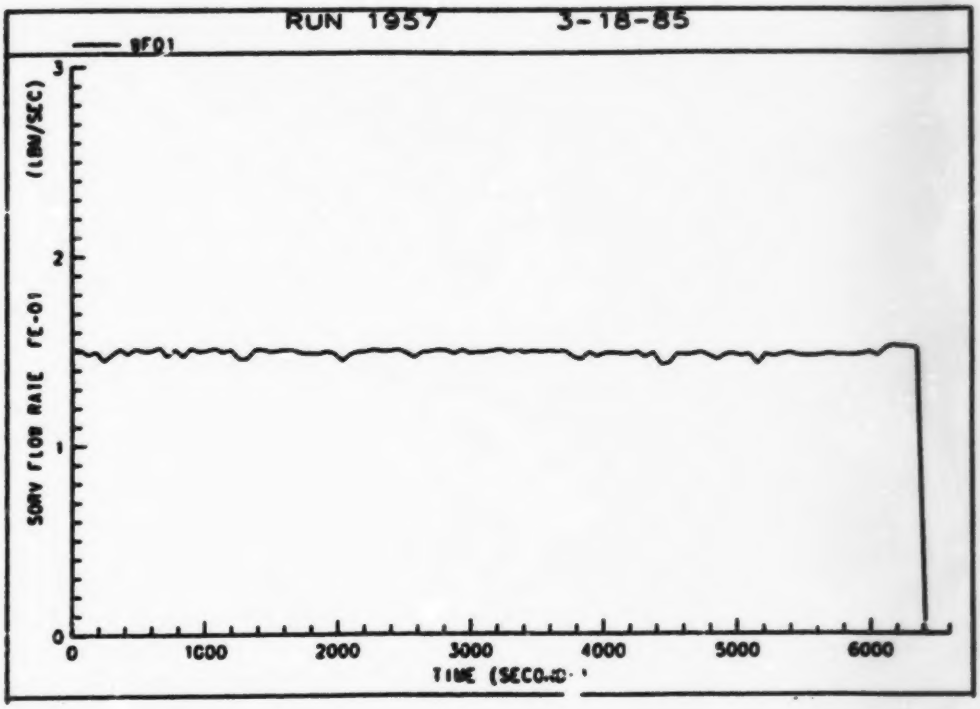

Figure 5-73. SORV Flow Rate (WF-01): Test No. 6 (T-1957)

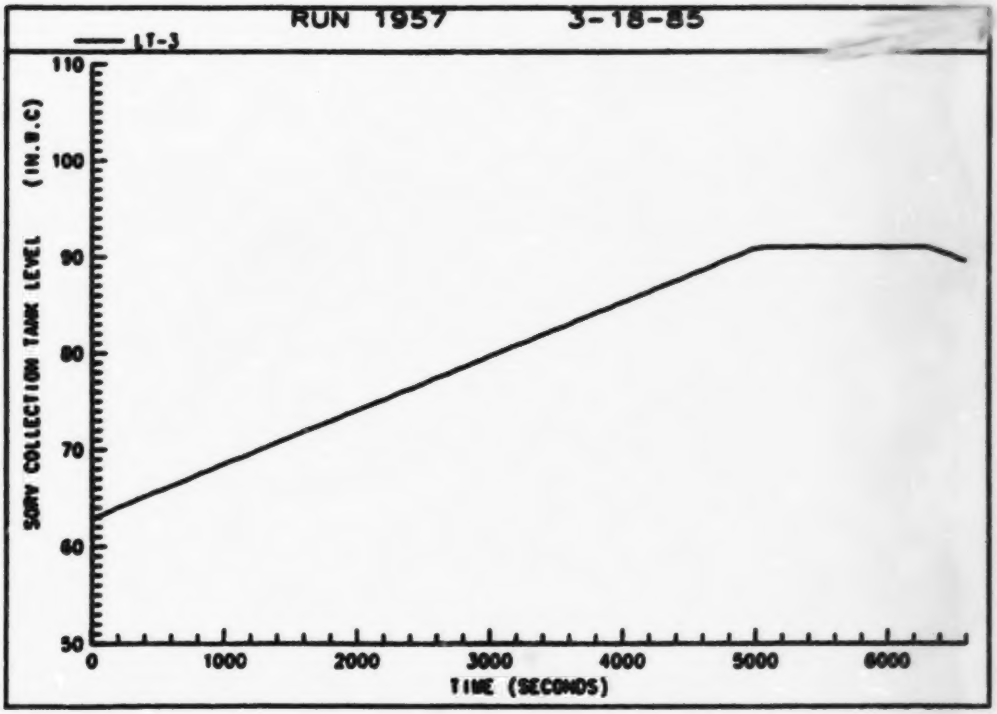

Figure 5-74. SORV Tank Level (LT-3): Test No. 6 (T-1957)

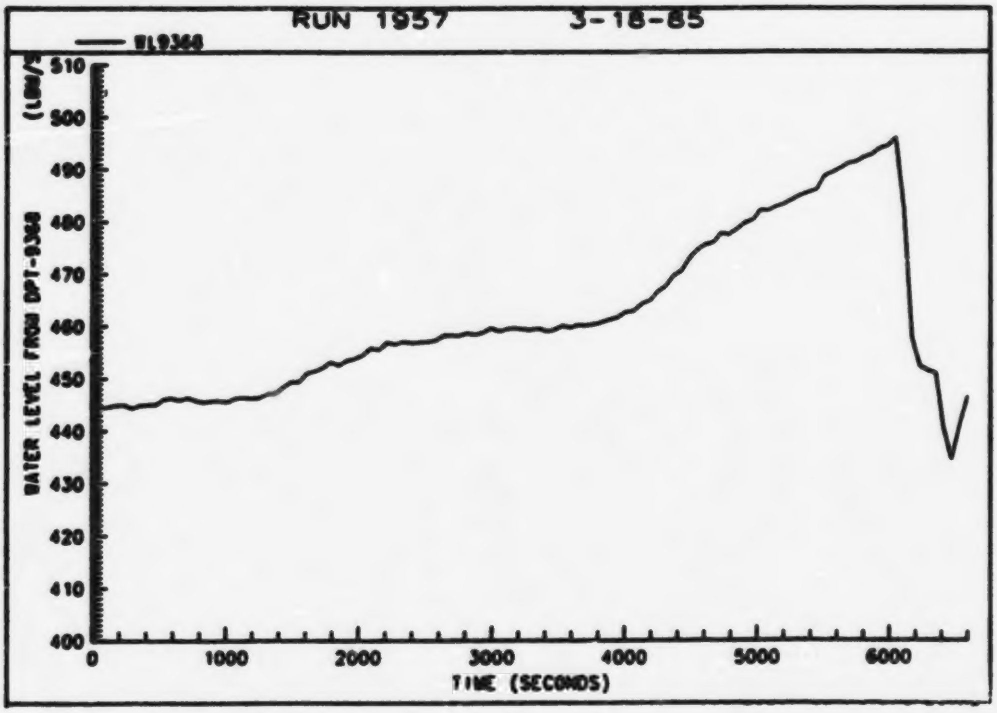

Figure 5-75. Downcomer Water Level - Narrow Range (WL-9368): Test No. 6 (T-1957)

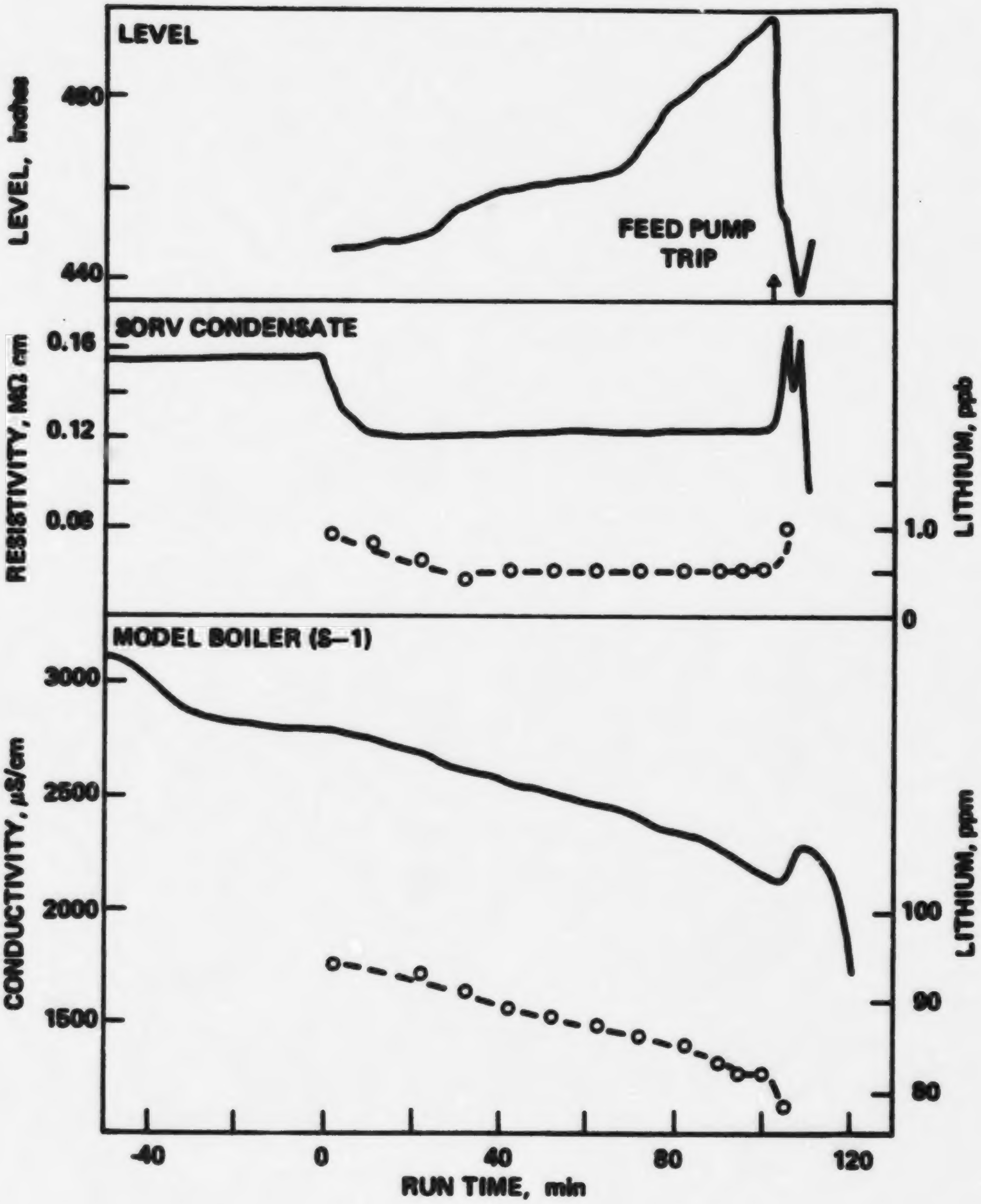

Figure 5-76. Variation in Tracer Concentrations: Test No. 6 (T-1957)

—— LEVEL, RESISTIVITY OR CONDUCTIVITY

—○— LITHIUM CONCENTRATION

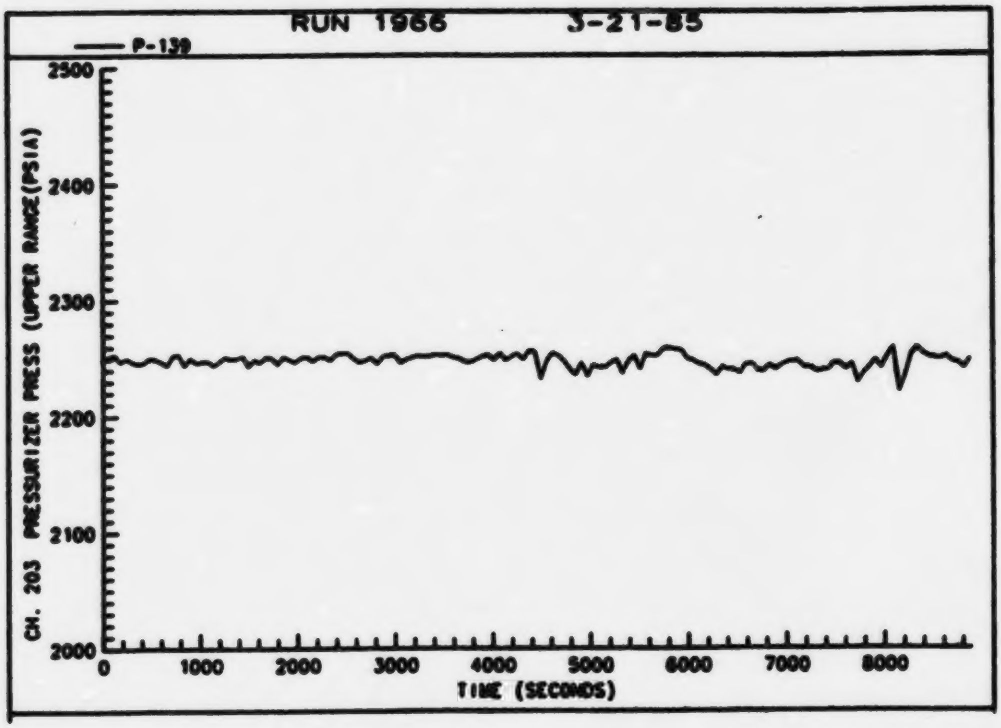

Figure 5-77. Primary System (Pressurizer) Pressure (P-139): Test No. 7 (T-1966)

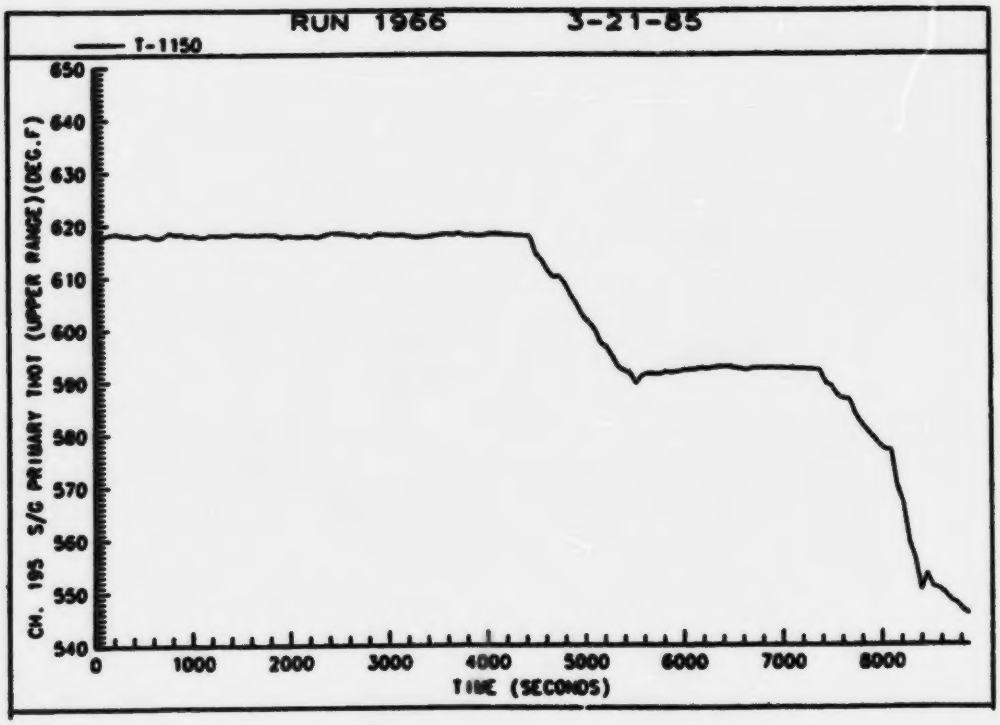

Figure 5-78. Primary Fluid T_{hot} (T-1150): Test No. 7 (T-1966)

228

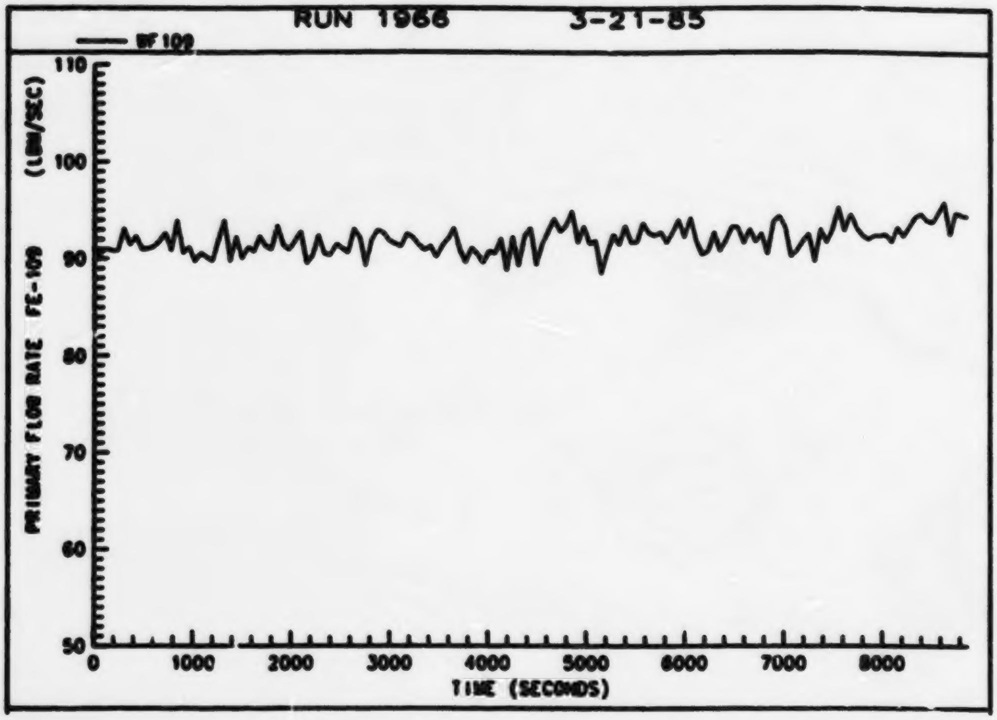

Figure 5-79. Primary Fluid Flow Rate (WF-109): Test No. 7 (T-1966)

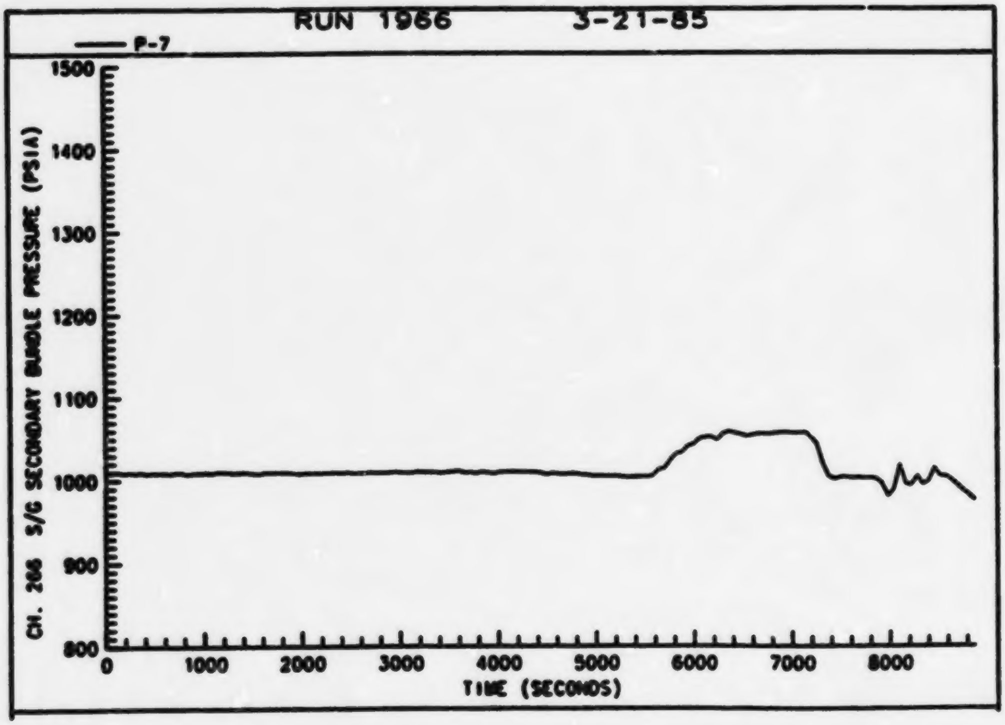

Figure 5-80. Secondary Side Pressure (P-7): Test No. 7 (T-1966)

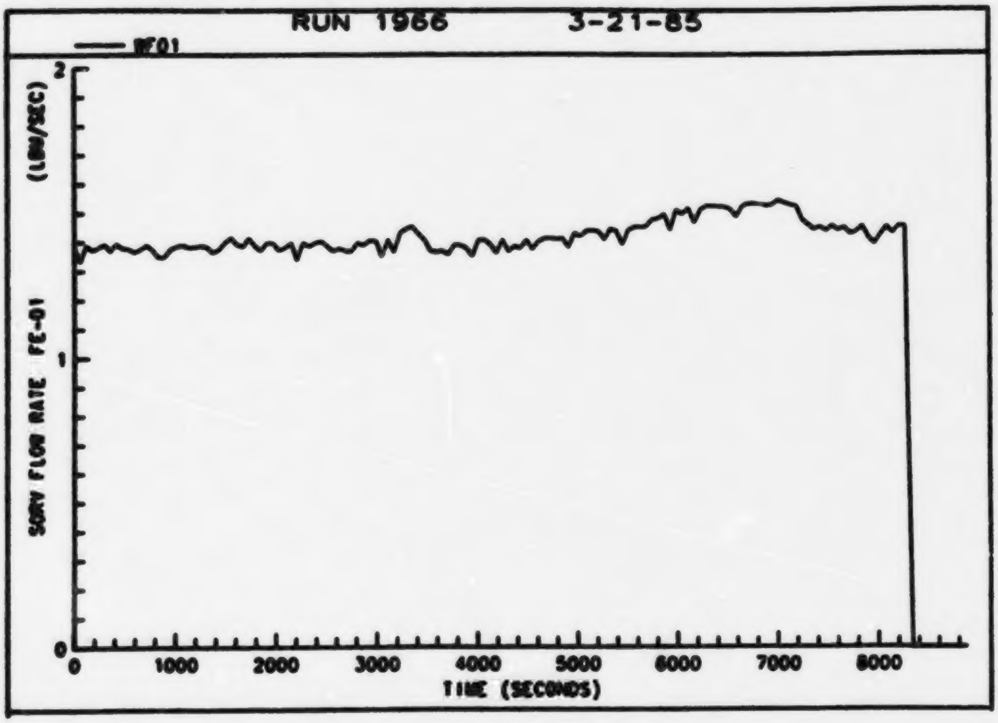

Figure 5-81. SORV Flow Rate (WF-01): Test No. 7 (T-1966)

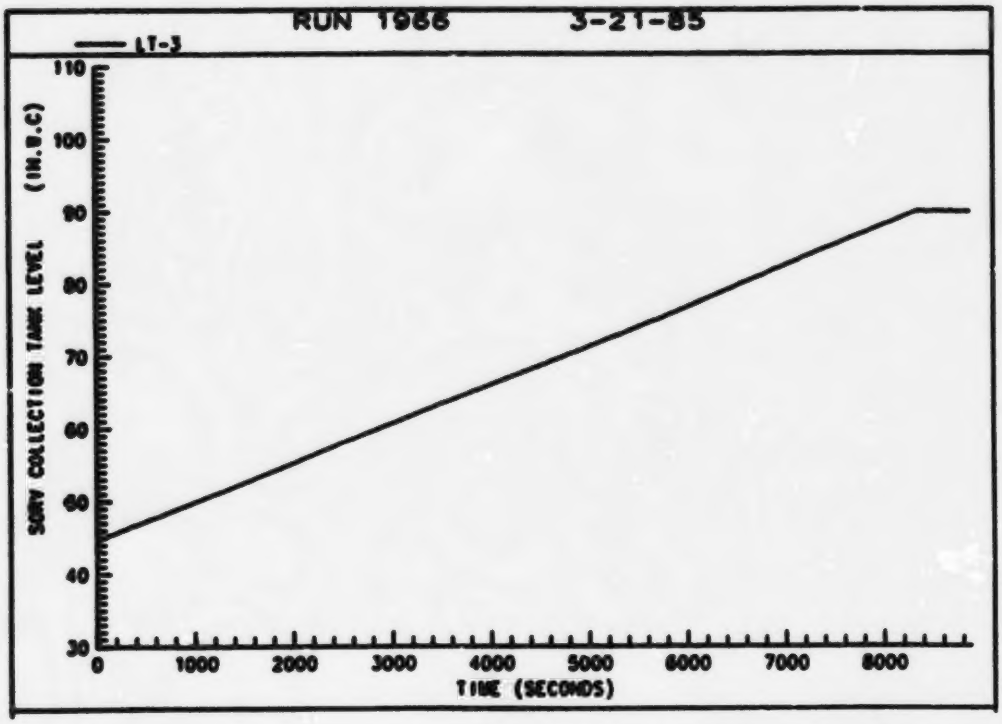

Figure 5-82. SORV Tank Level (LT-3): Test No. 7 (T-1966)

230

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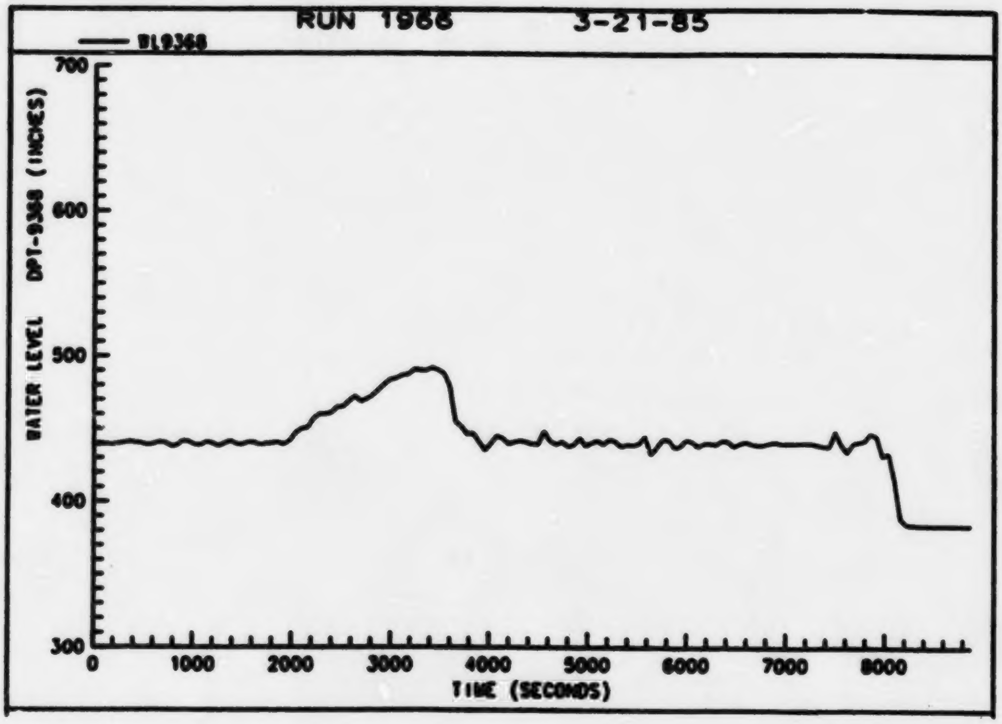

Figure 5-83. Downcomer Water Level - Narrow Range (WL-9268): Test No. 7 (T-1966)

231

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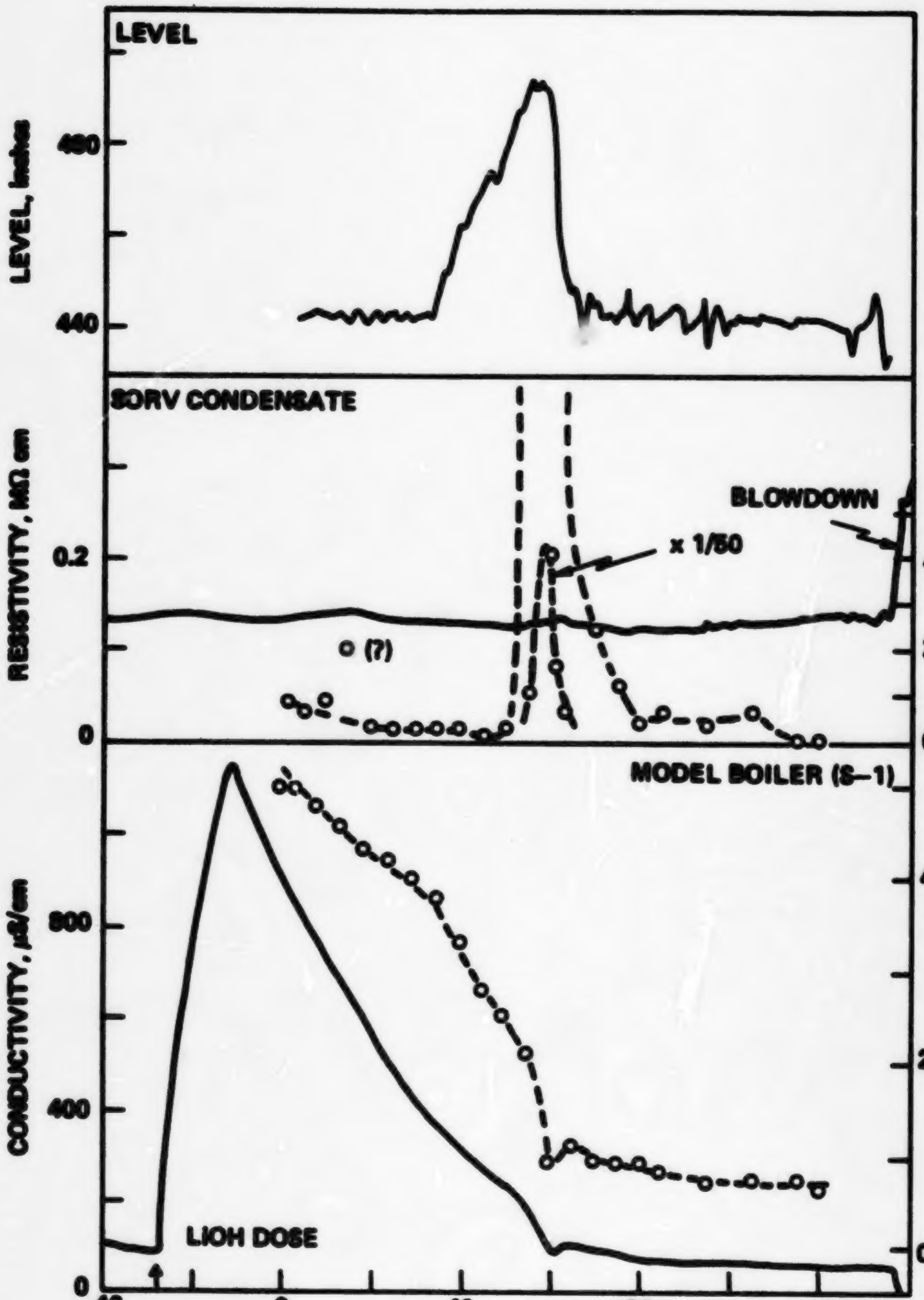

Figure 5-84. Variation in Tracer Concentrations: Test No. 7 (T-1966)

232

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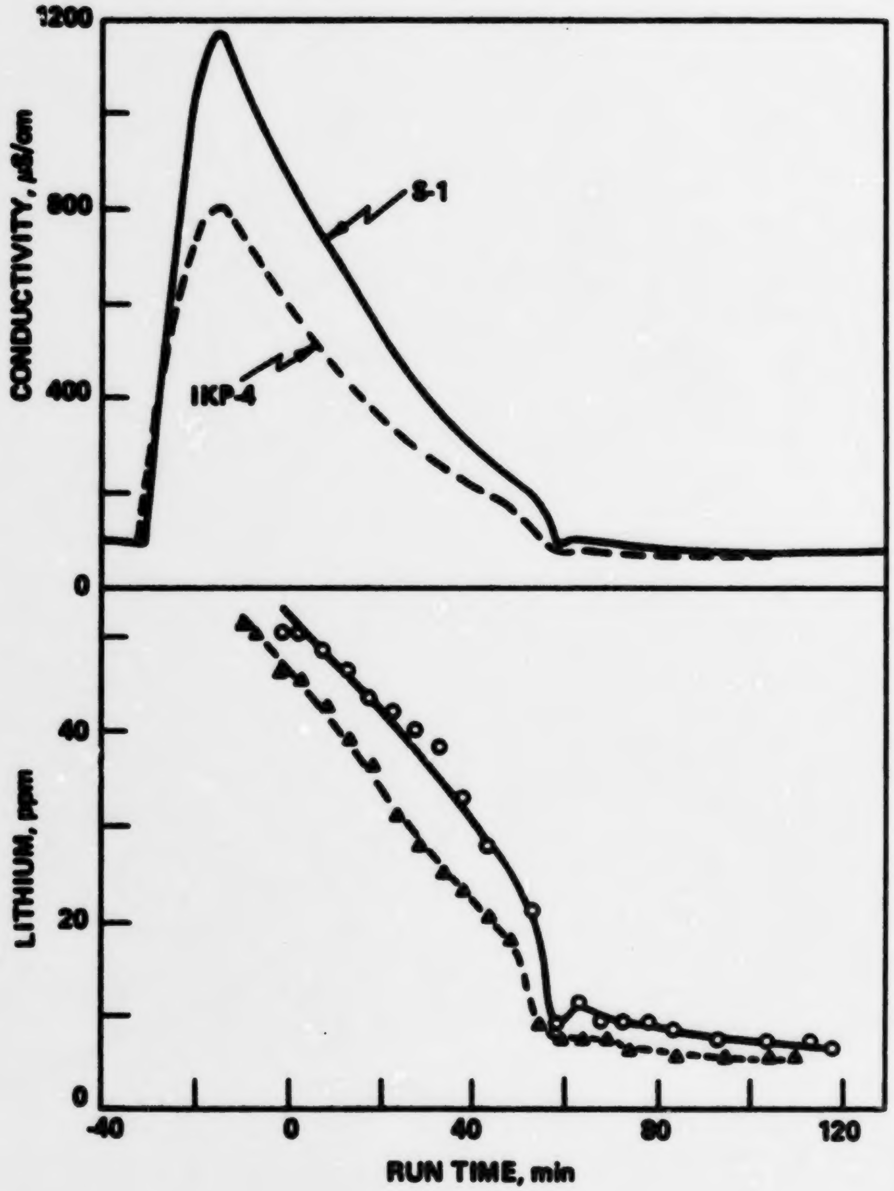

Figure 5-85. Comparison Between S-1 (○) and IKP-4 (▲) Results After Correcting for Sample Line Delays: Test No. 7 (T-1966)

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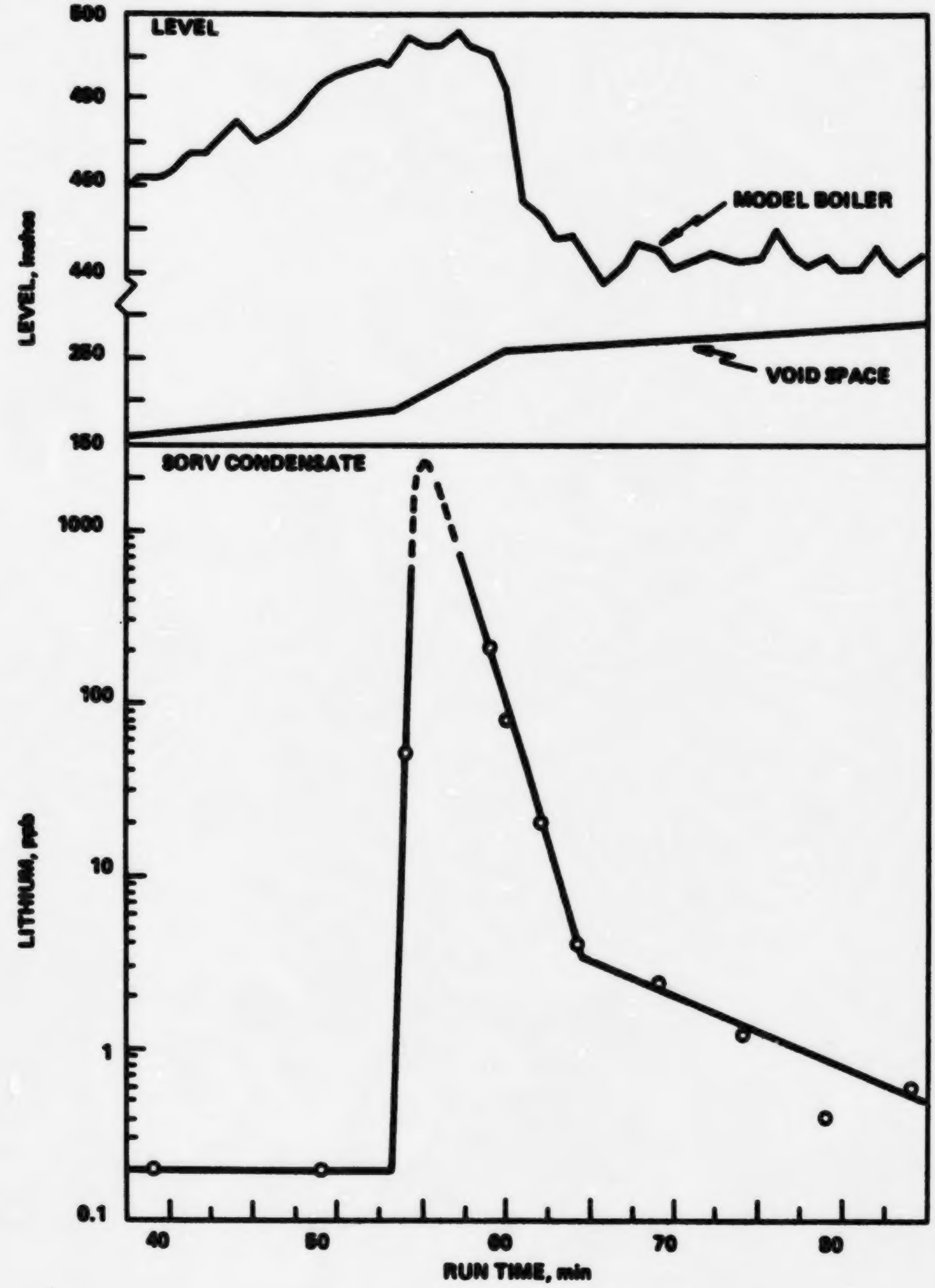

Figure 5-86. Comparison Between SORV Condensate Results with Model Boiler Water Levels After Correcting for Sample Line Delays: Test No. 7 (T-1966)

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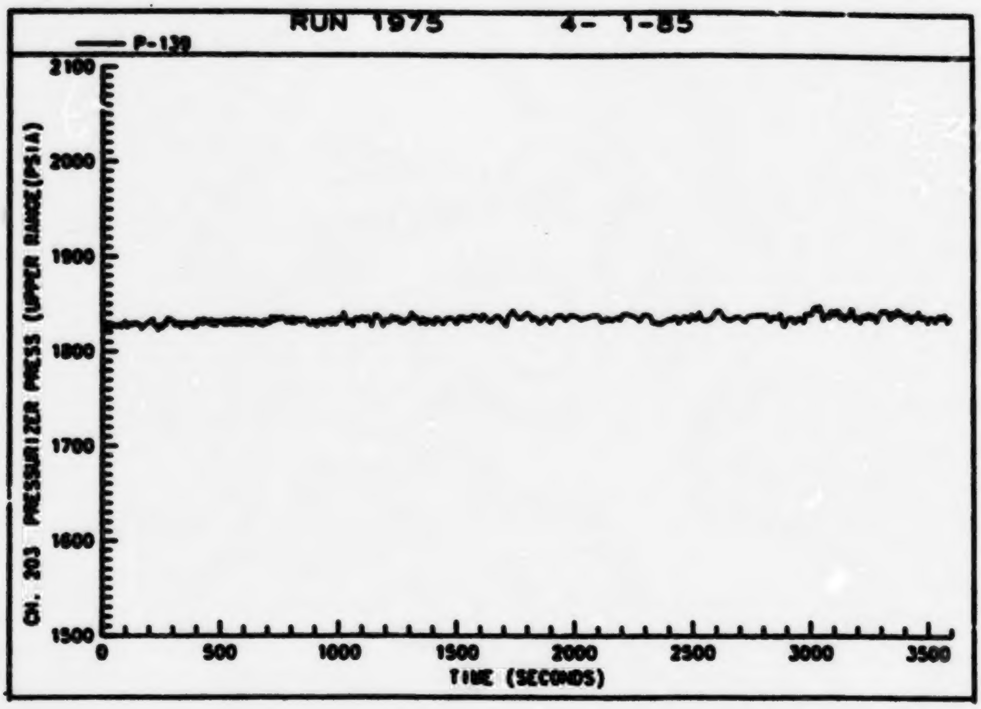

Figure 5-87. Primary System (Pressurizer) Pressure (P-139): Test 8 (T-1975)

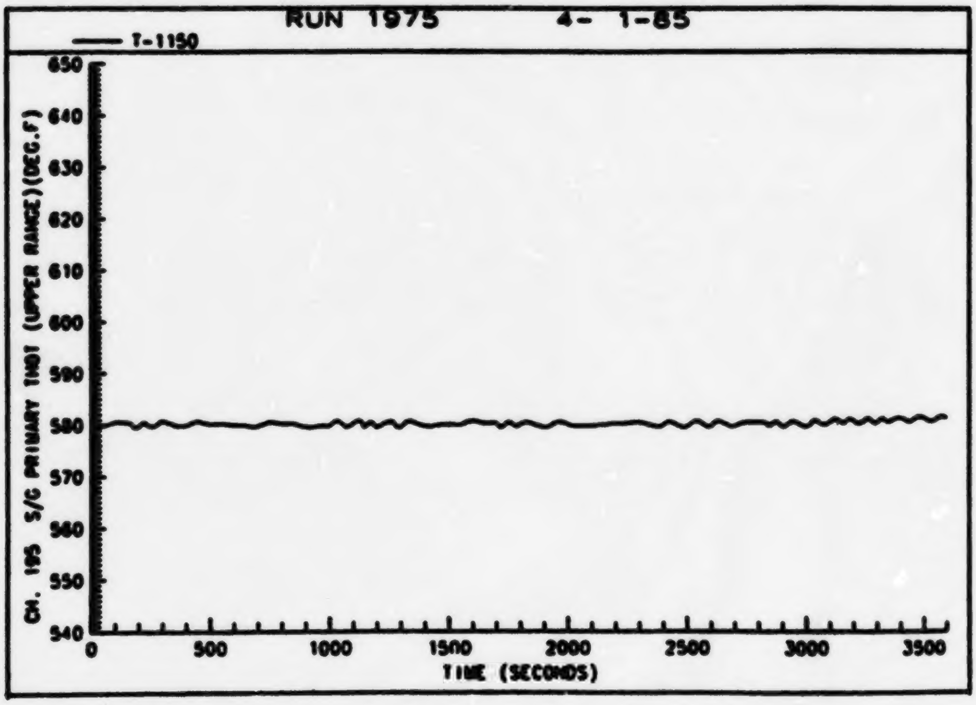

Figure 5-88. Primary Fluid T_{hot} (T-1150): Test No. 8 (T-1975)

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235

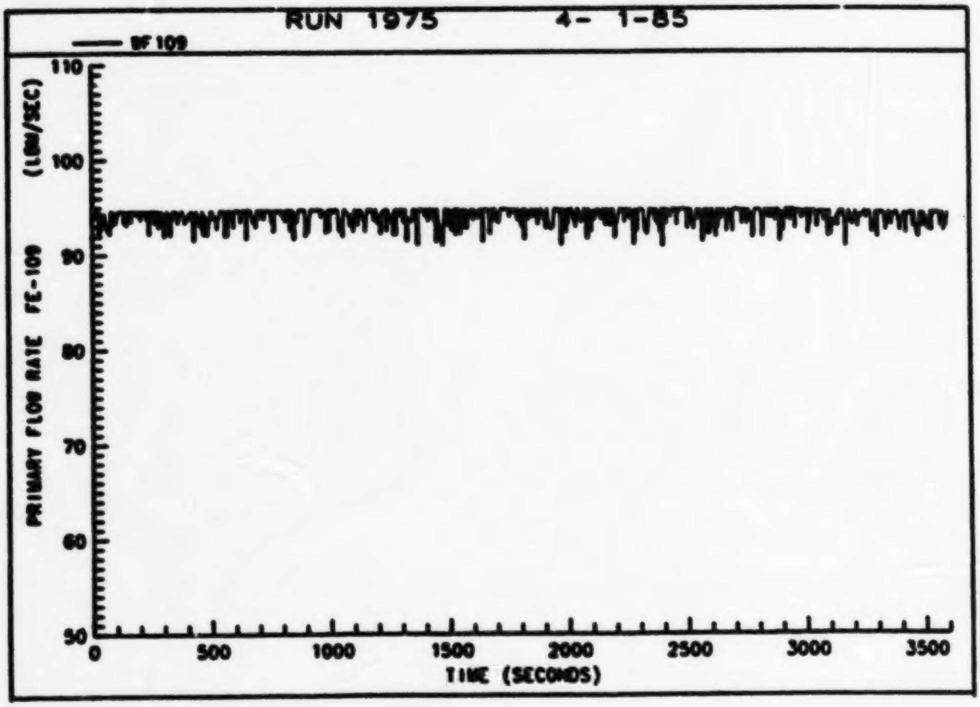

Figure 5-89. Primary Fluid Flow Rate (WF-109):Test No. 8 (T-1975)

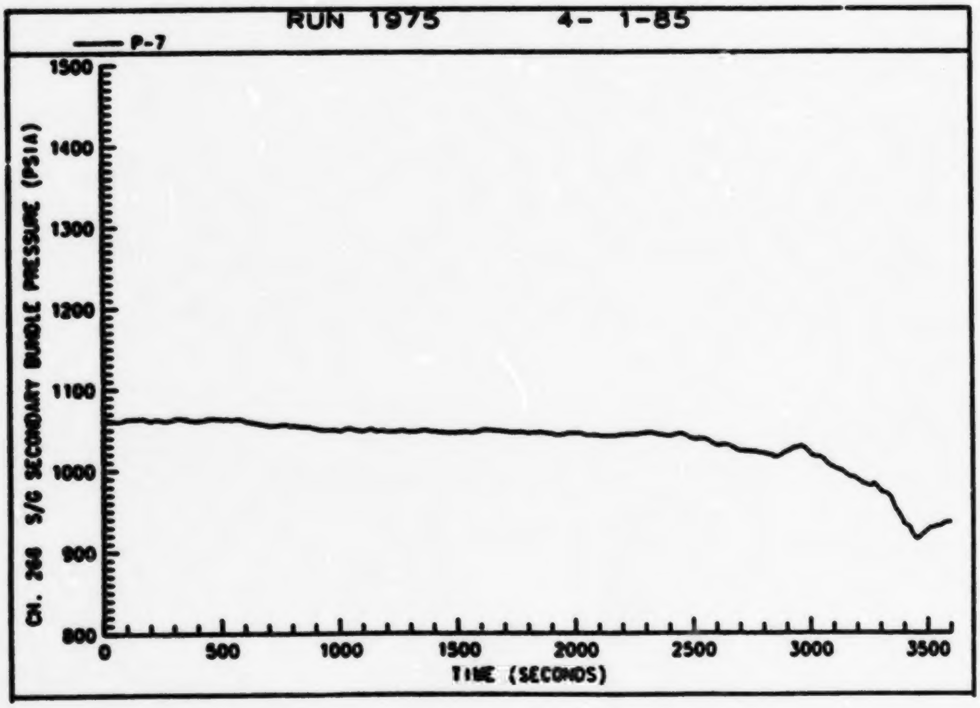

Figure 5-90. Secondary Side Pressure (P-7):Test No. 8 (T-1975)

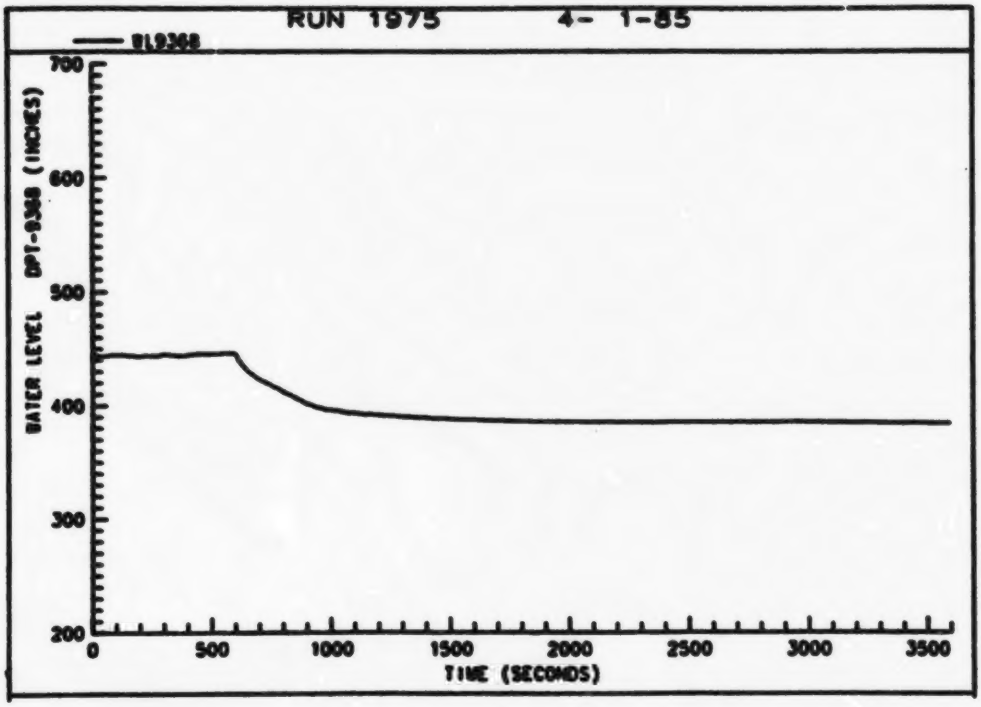

Figure 5-91. Downcomer Water Level - Narrow Range (WL-9368): Test No. 8 (T-1975)

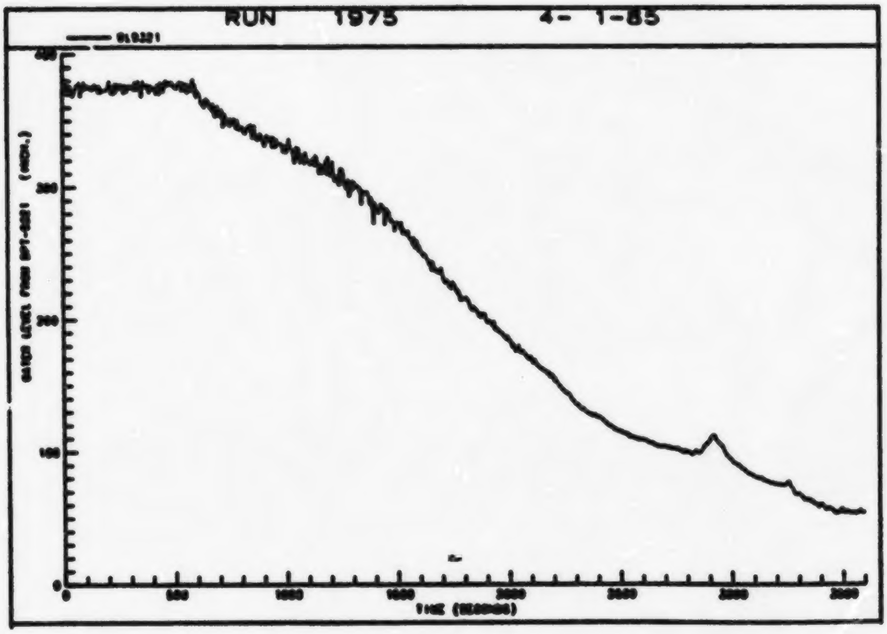

Figure 5-92. Downcomer Water Level - Wide Range (WL-9321): Test No. 8 (T-1975)

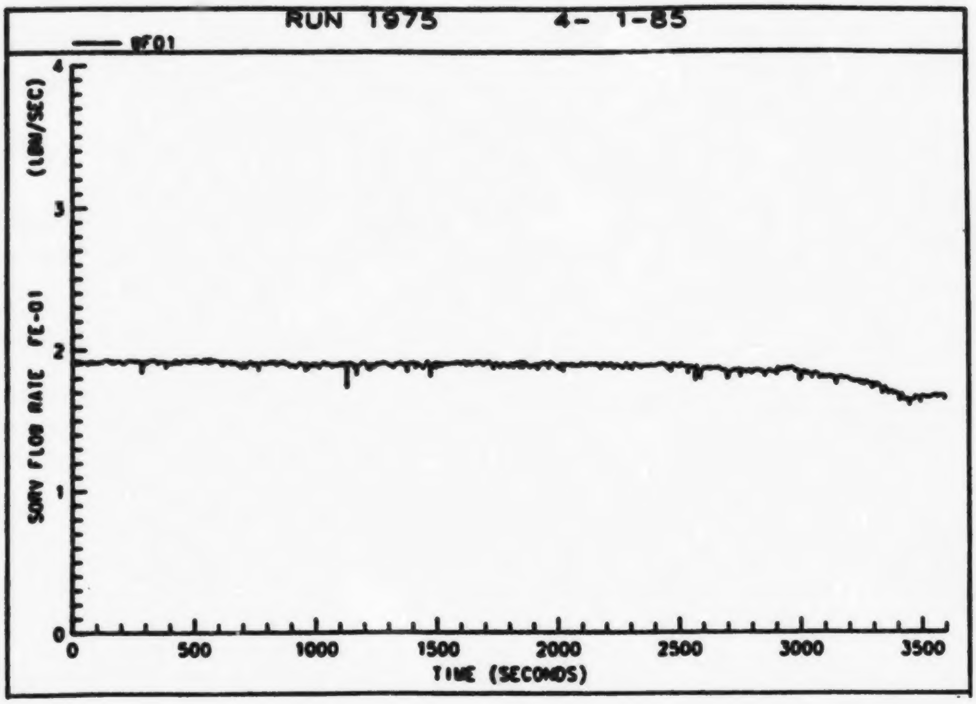

Figure 5-93. SORV Flow Rate (WF-01): Test No. 8 (T-1975)

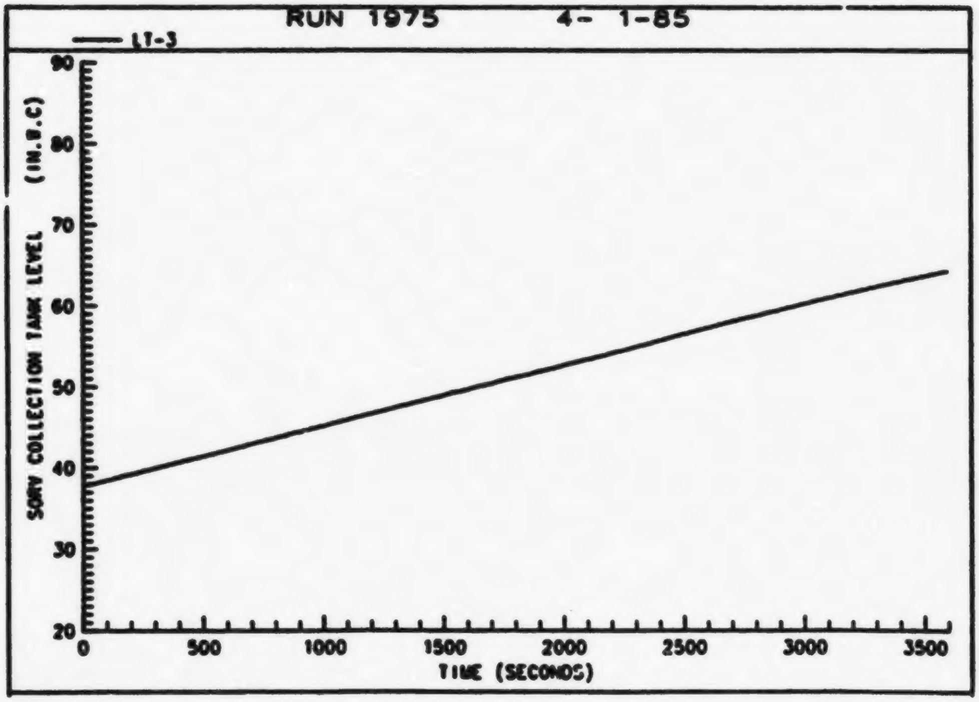

Figure 5-94. SORV Tank Level (LT-3): Test No. 8 (T-1975)

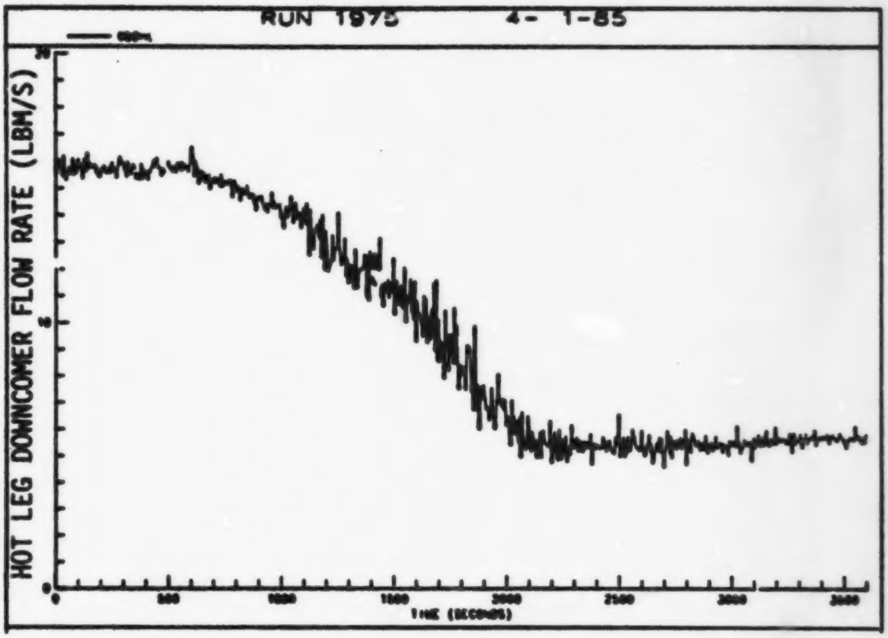

Figure 5-95. Hot Leg Downcomer Flow Rate (WDCHL): Test No. 8 (T-1975)

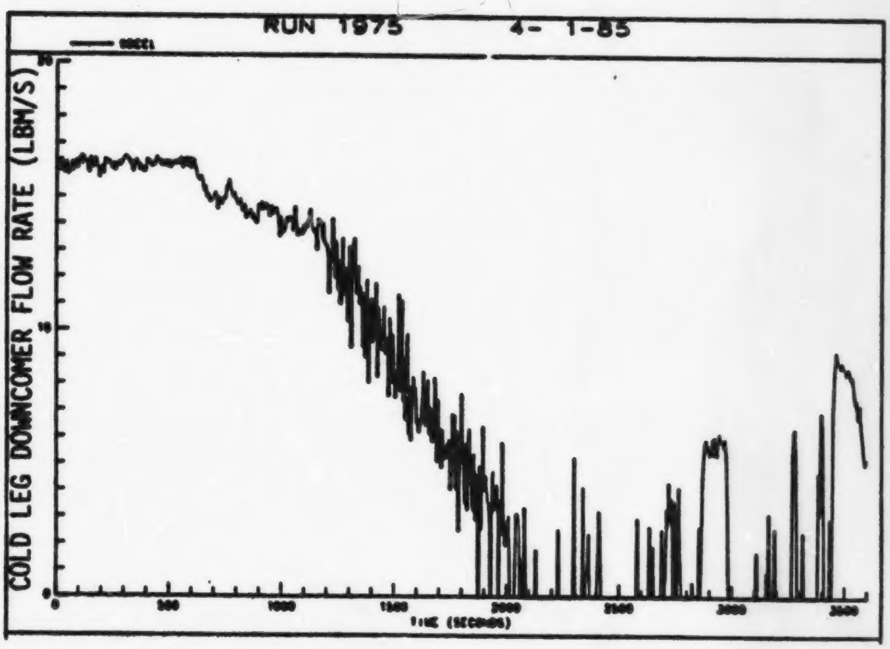

Figure 5-96. Cold Leg Downcomer Flow Rate (WOCCL): Test No. 8 (T-1975)

239

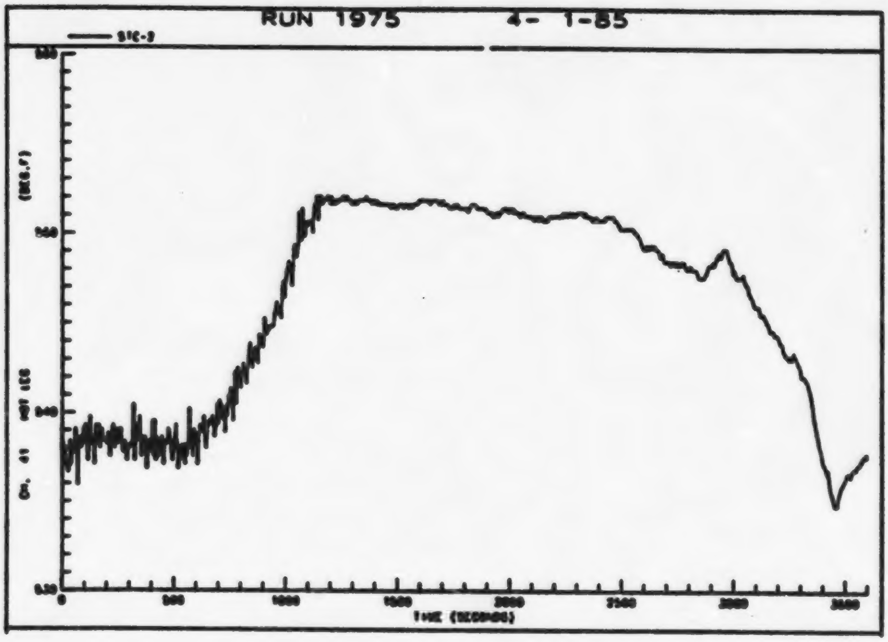

Figure 5-97. Secondary Fluid Temperature (STC-2): Test No. 8 (T-1975)

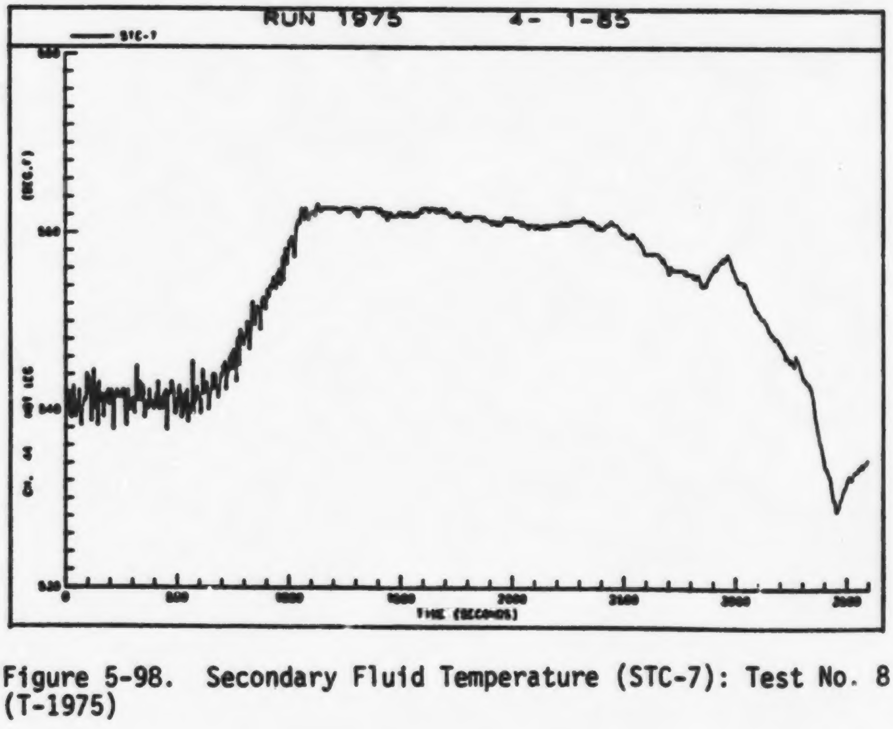

Figure 5-98. Secondary Fluid Temperature (STC-7): Test No. 8 (T-1975)

240

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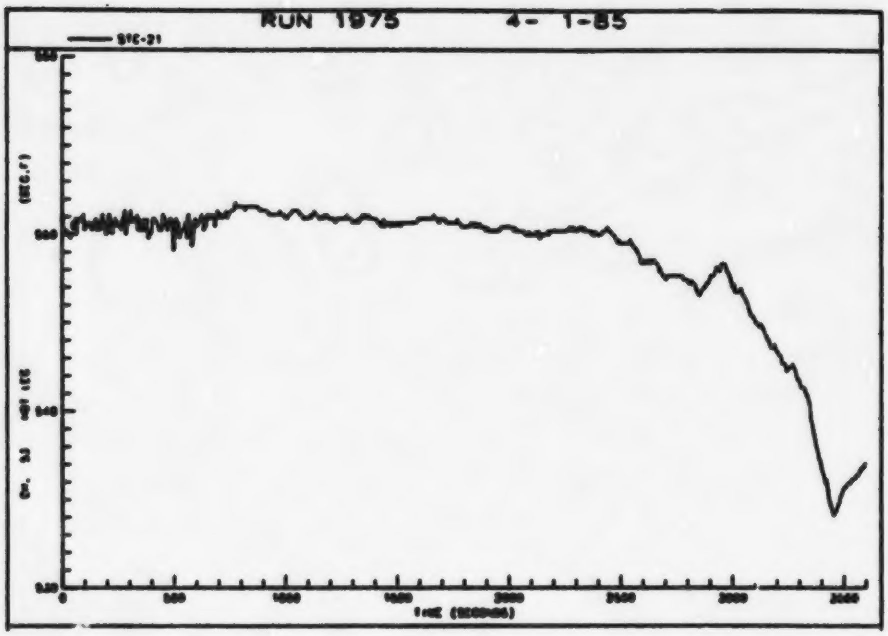

Figure 5-99. Secondary Fluid Temperature (STC-21): Test No. 8 (T-1975)

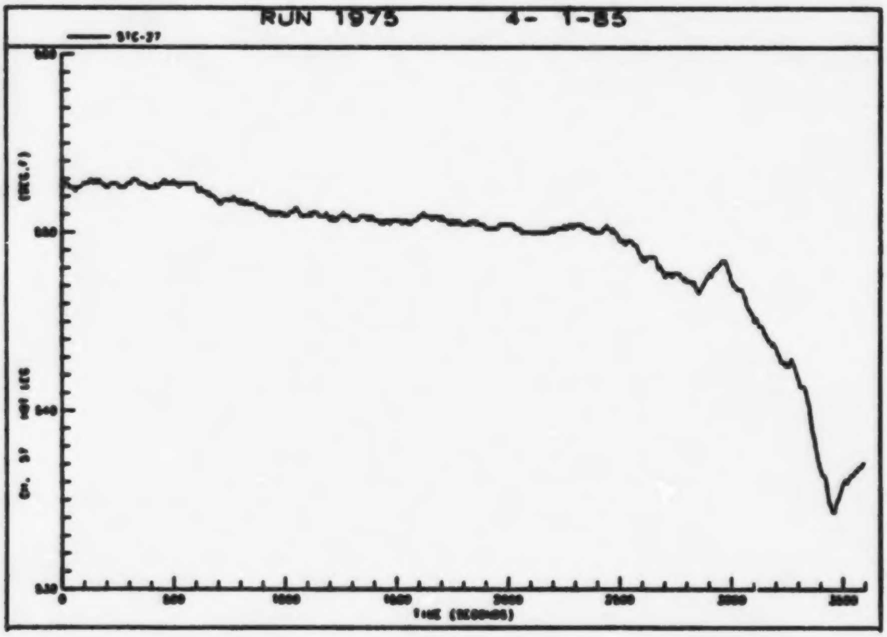

Figure 5-100. Secondary Fluid Temperature (STC-27): Test No. 8 (T-1975)

241

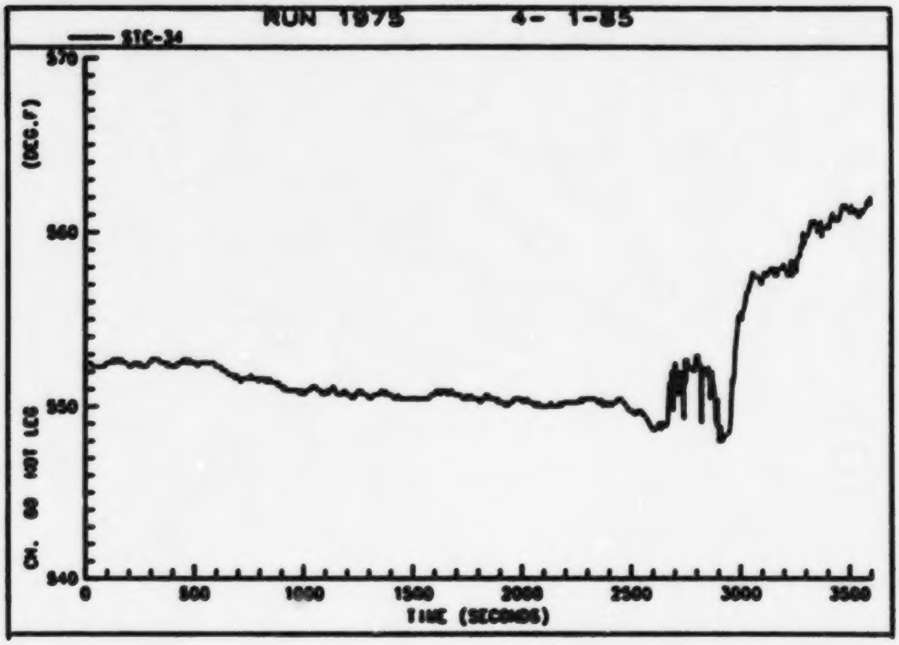

Figure 5-101. Secondary Fluid Temperature (STC-34): Test No. 8 (T-1975)

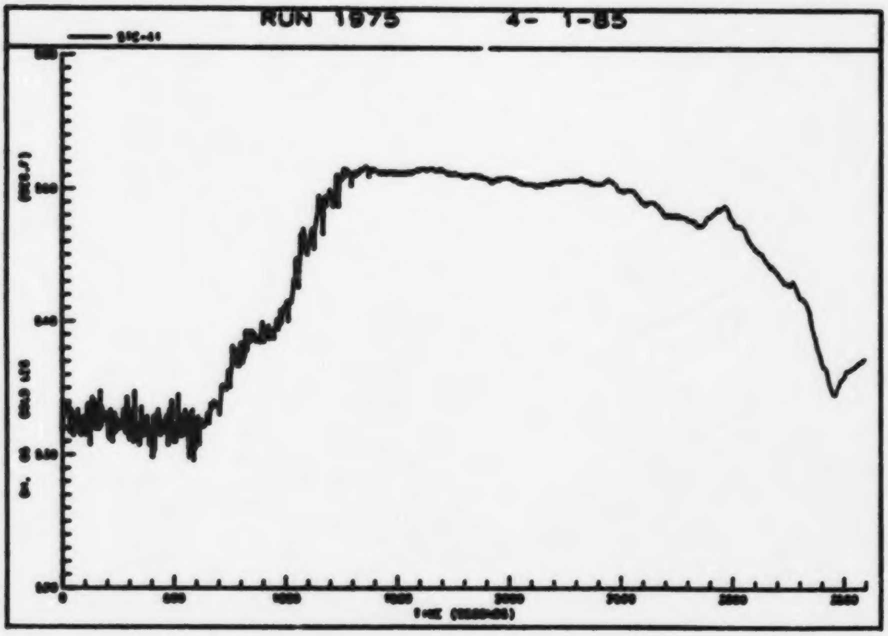

Figure 5-102. Secondary Fluid Temperature (STC-41): Test No. 8 (T-1975)

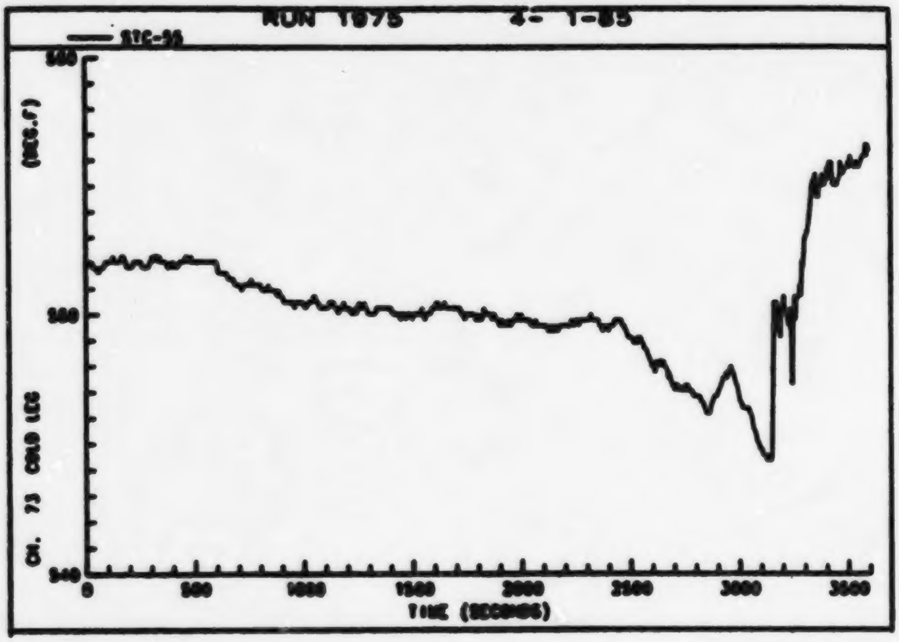

Figure 5-103. Secondary Fluid Temperature (STC-55): Test No. 8 (T-1975)

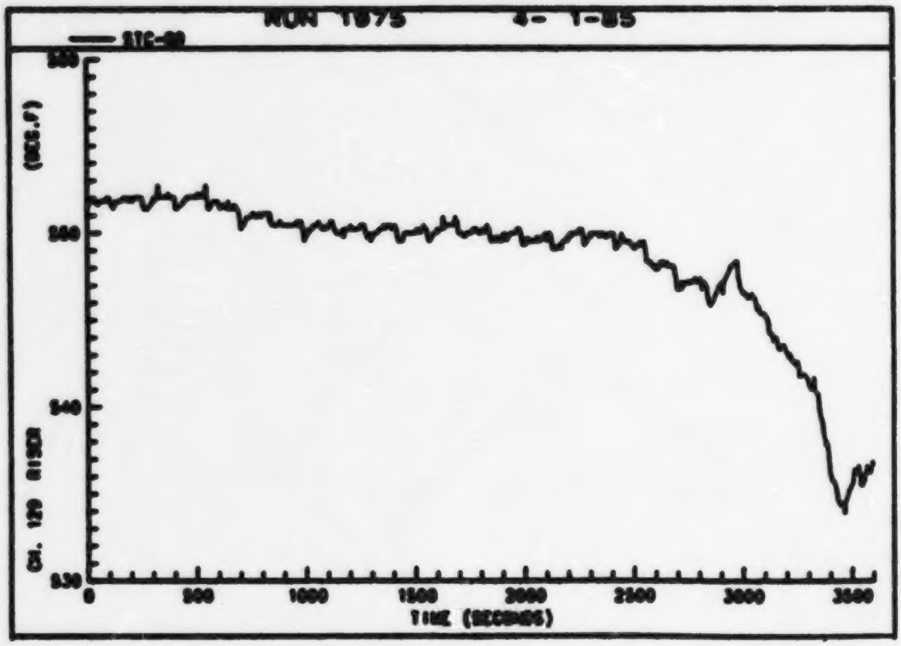

Figure 5-104. Secondary Fluid Temperature (STC-60): Test No. 8 (T-1975)

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243

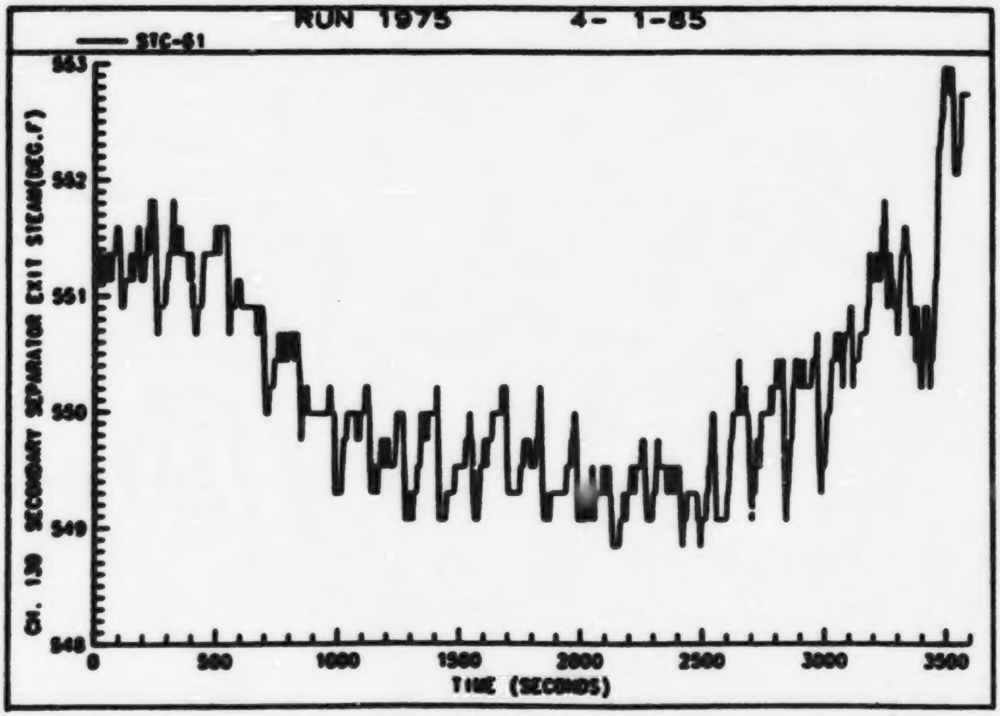

Figure 5-105. Secondary Fluid Temperature (STC-61):
Test No. 8 (T-1975)

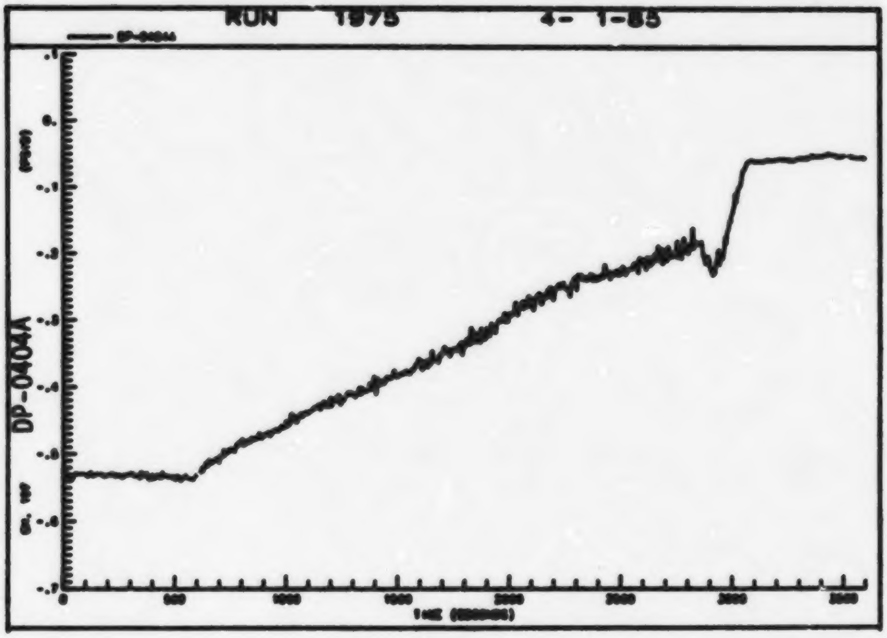

Figure 5-106. Differential Pressure, DP-0404A:
Test No. 8 (T-1975)

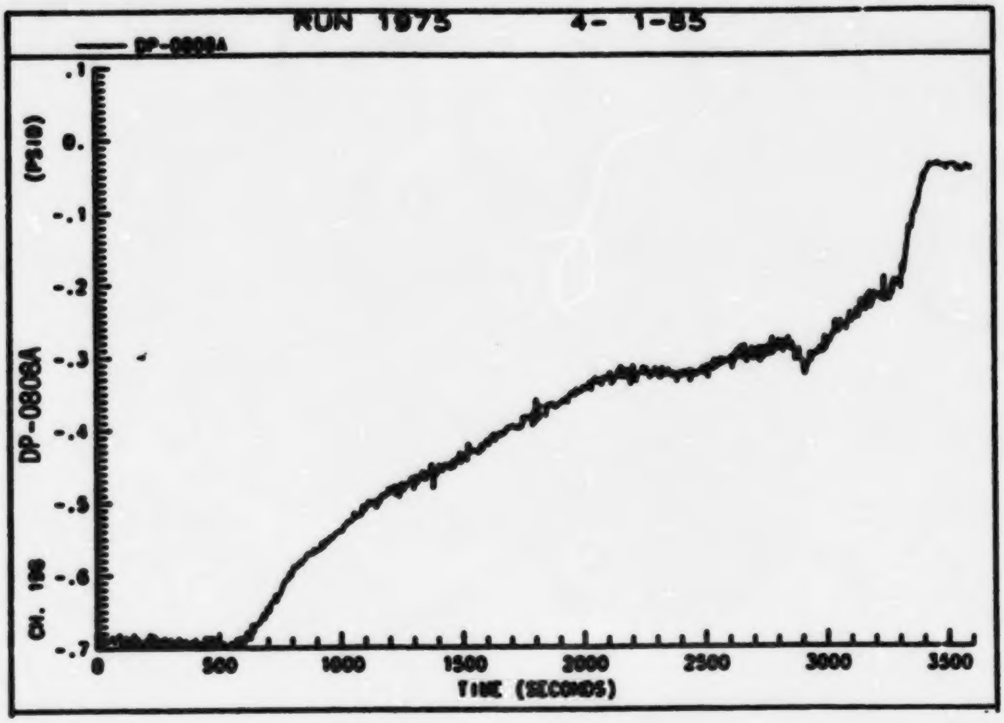

Figure 5-107. Differential Pressure, DP-0808A: Test No. 8 (T-1975)

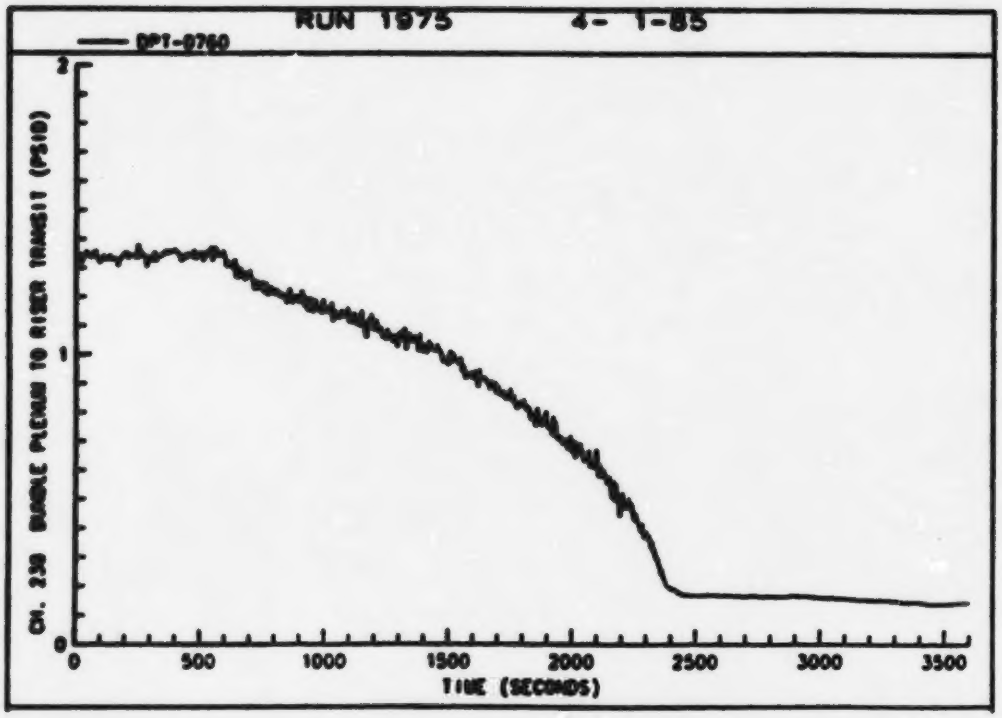

Figure 5-108. Differential Pressure, DP-0760: Test No. 8 (T-1975)

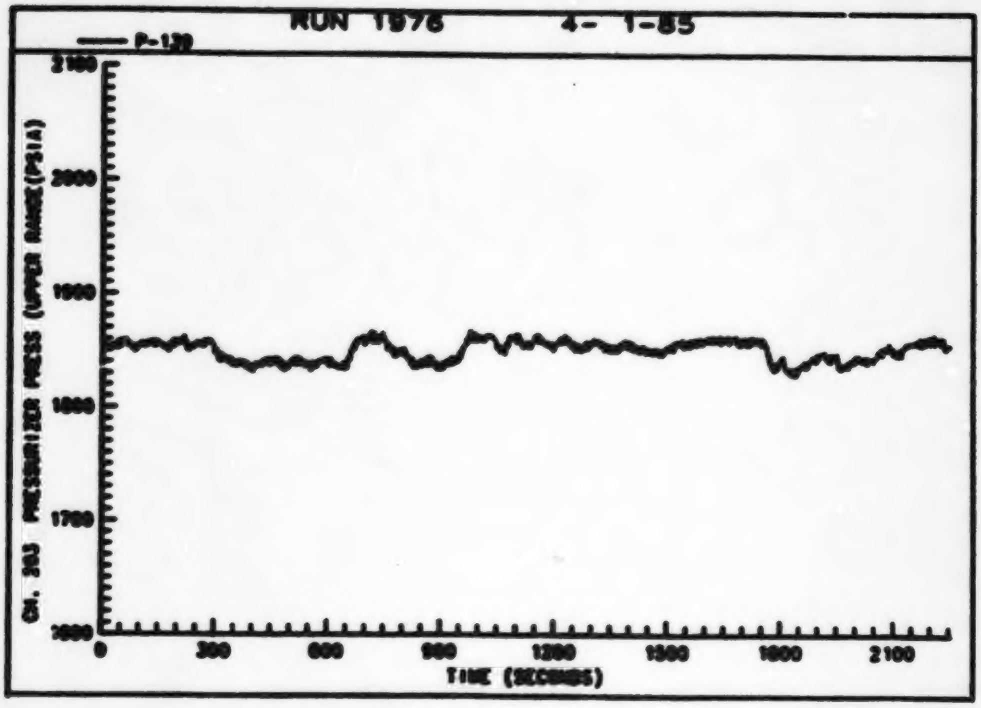

Figure 5-109. Primary System (Pressurizer) Pressure (P-139): Test No. 8 (T-1976)

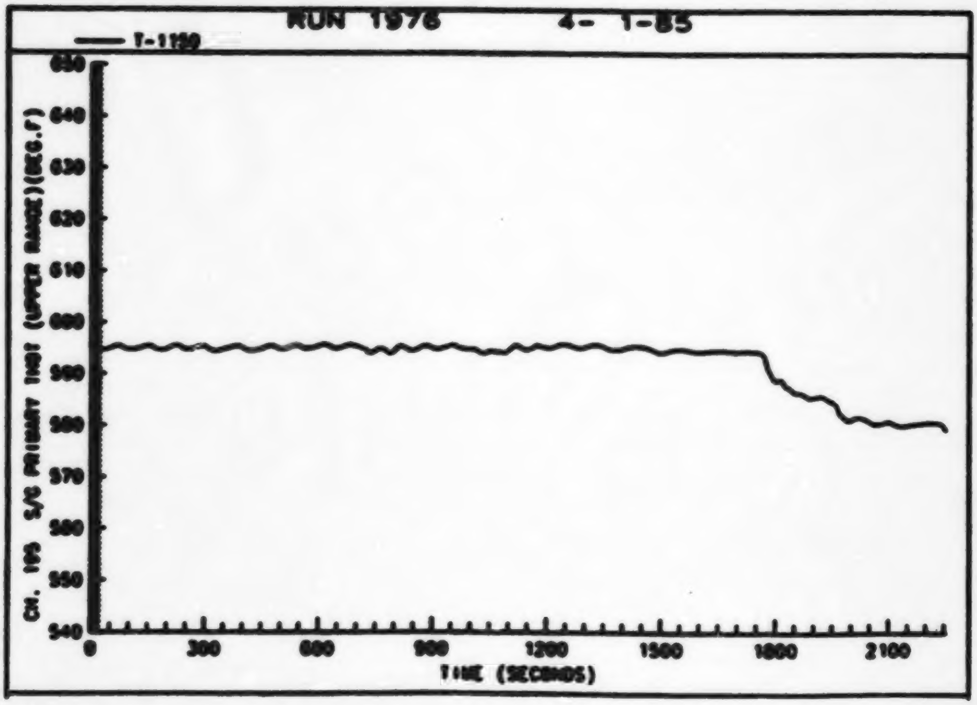

Figure 5-110. Primary Fluid T_{hot} (T-1150): Test No. 8 (T-1976)

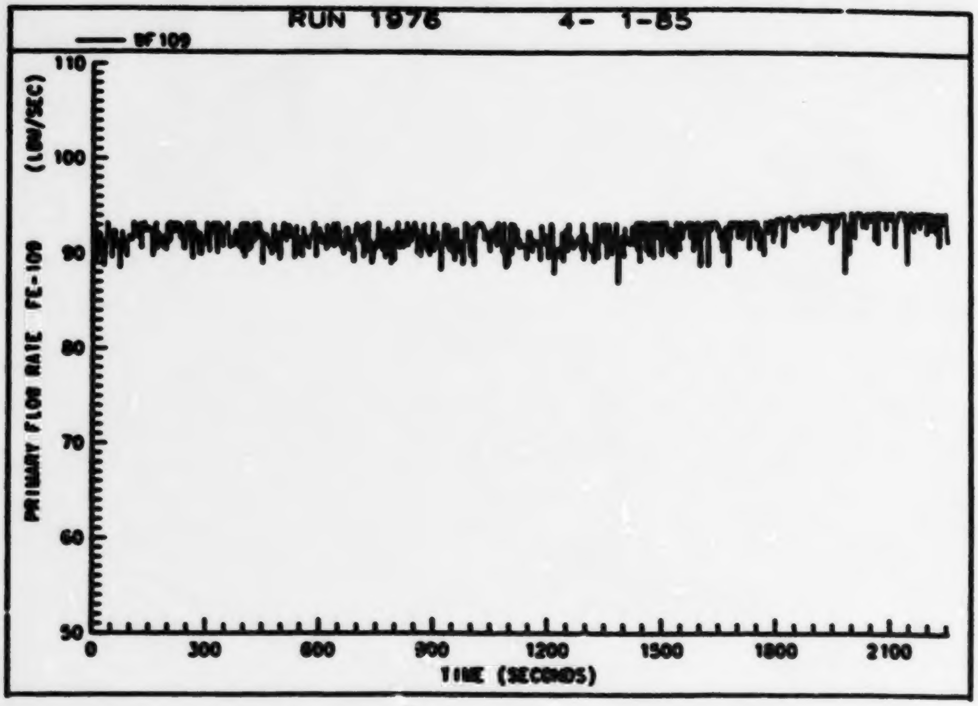

Figure 5-111. Primary Fluid Flow Rate (WF-109): Test No. 8 (T-1976)

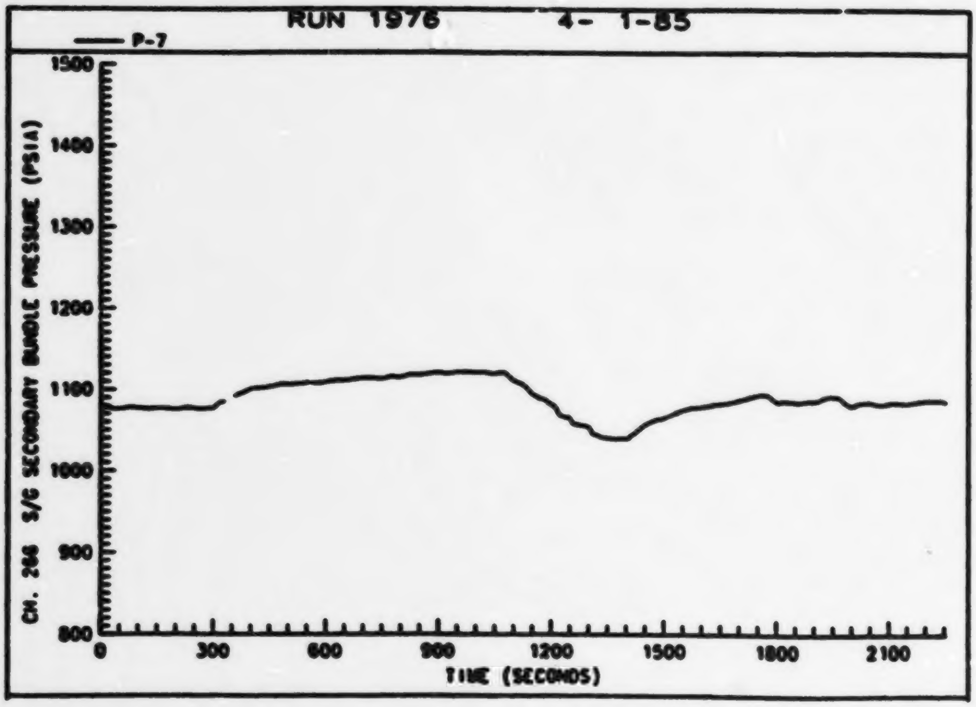

Figure 5-112. Secondary Side Pressure (P-7): Test No. 8 (T-1976)

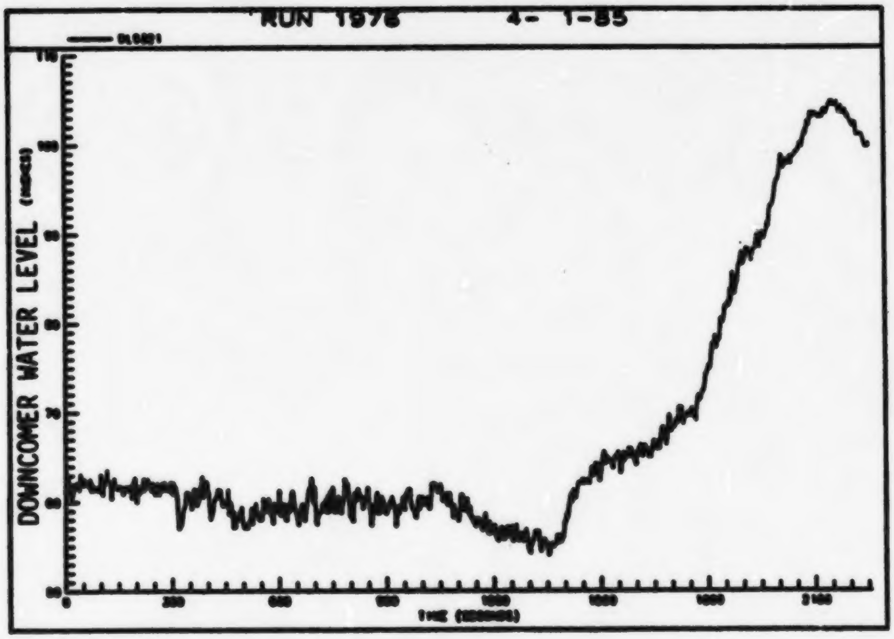

Figure 5-113. Downcomer Water Level - Wide Range (WL-9321): Test No. 8 (T-1976)

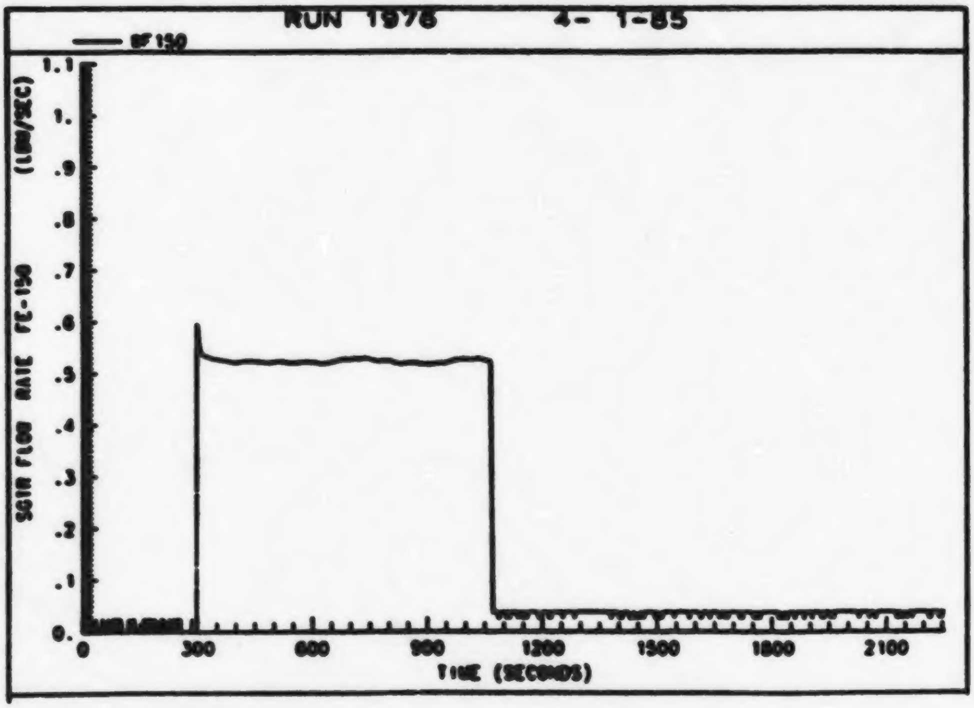

Figure 5-114. SGTR Flow Rate (WF-150): Test No. 8 (T-1976)

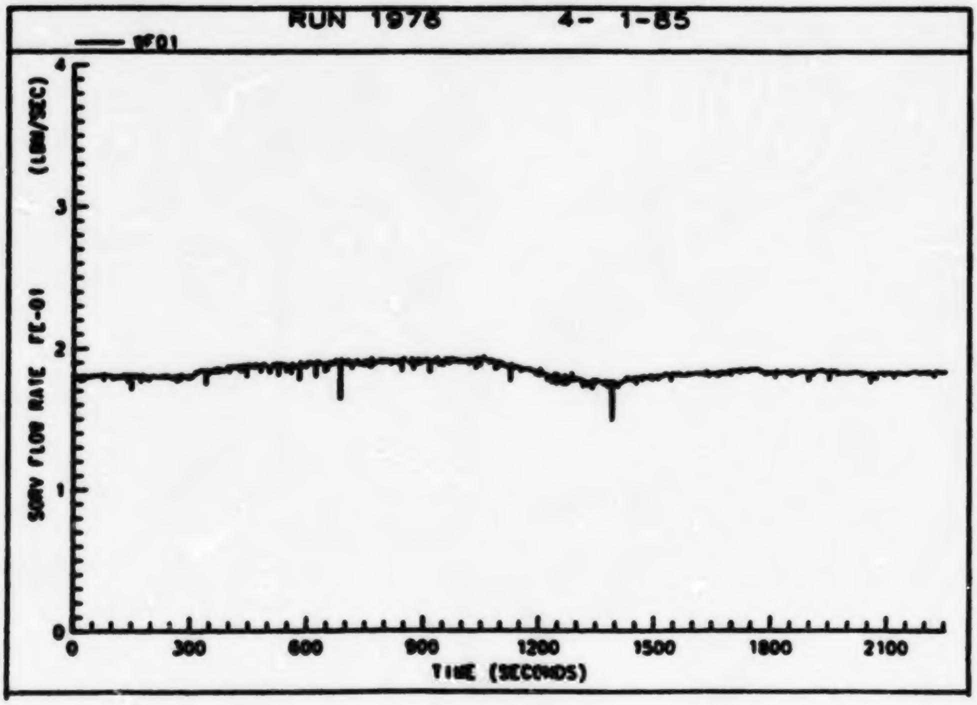

Figure 5-115. SORV Flow Rate (WF-01): Test No. 8 (T-1976)

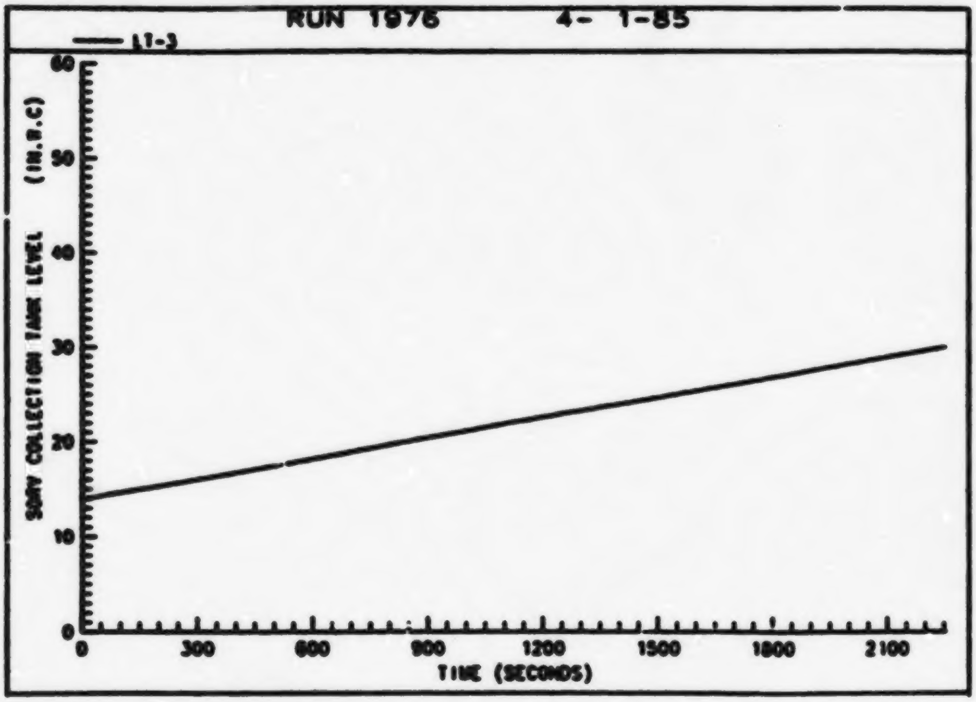

Figure 5-116. SORV Tank Level (LT-3): Test No. 8 (T-1976)

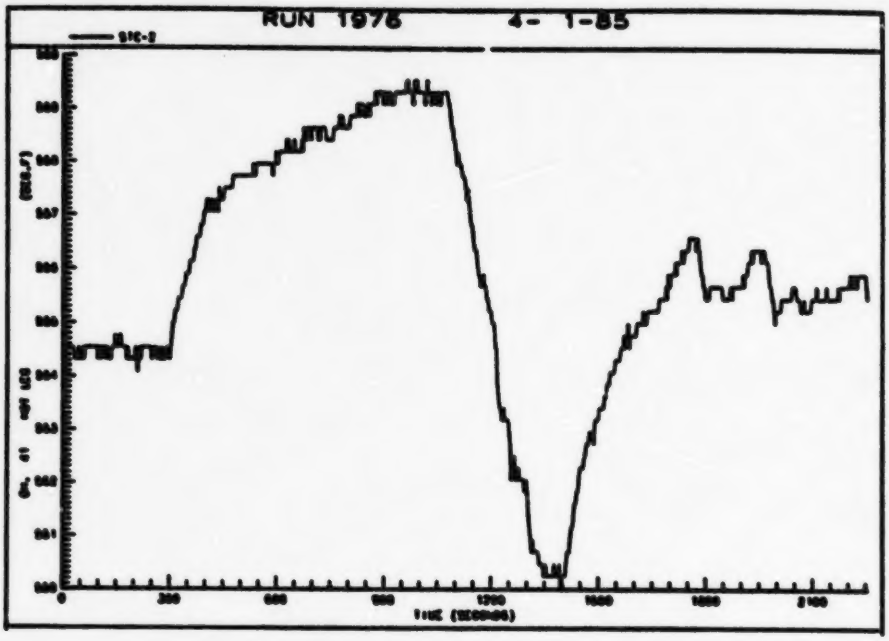

Figure 5-117. Secondary Fluid Temperature (STC-2): Test No. 8 (T-1976)

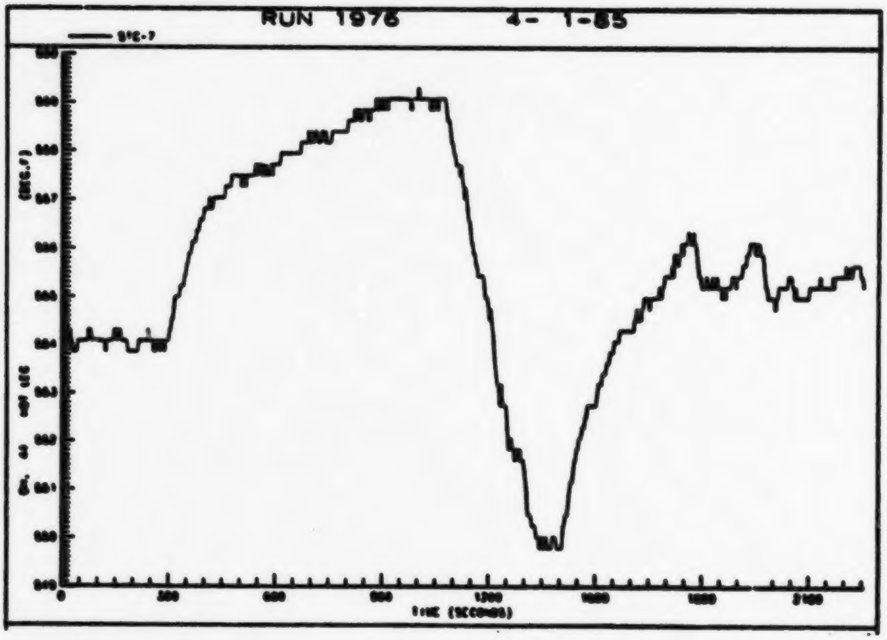

Figure 5-118. Secondary Fluid Temperature (STC-7): Test No. 8 (T-1976)

250

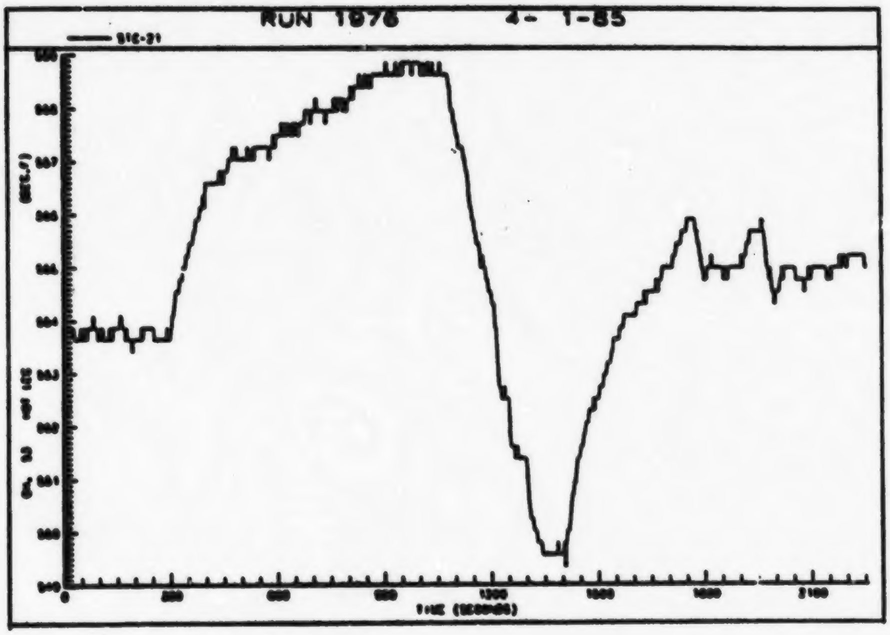

Figure 5-119. Secondary Fluid Temperature (STC-21): Test No. 8 (T-1976)

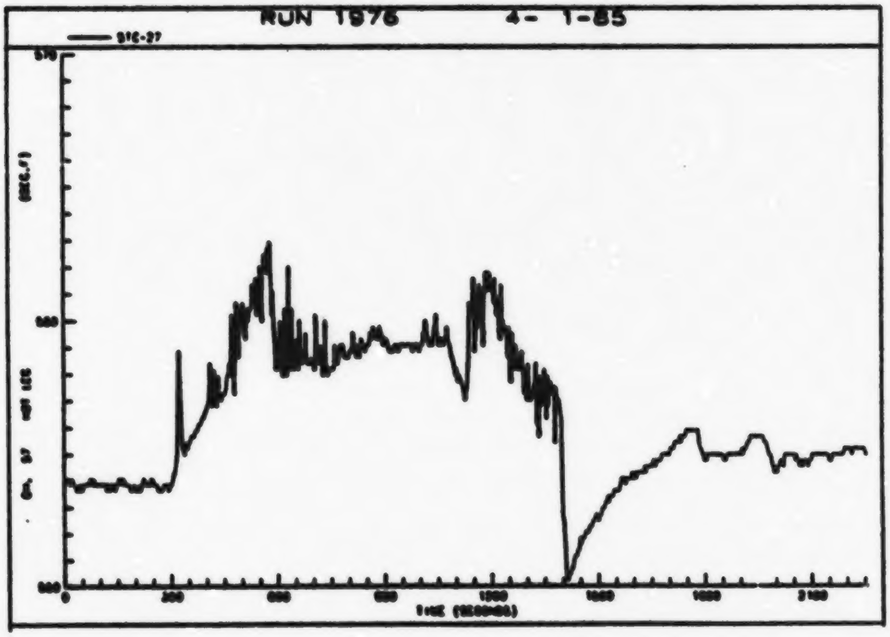

Figure 5-120. Secondary Fluid Temperature (STC-27): Test No. 8 (T-1976)

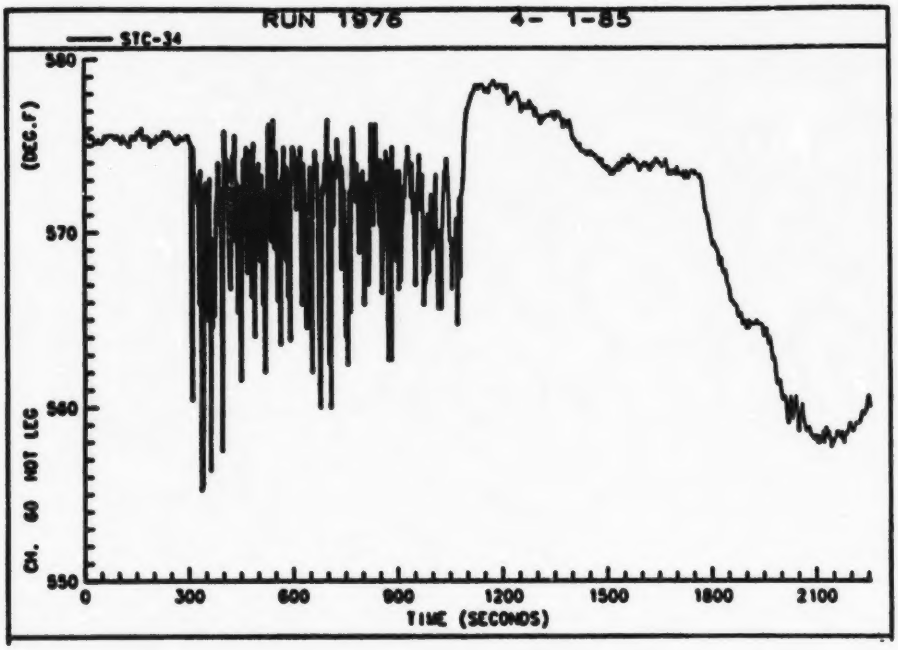

Figure 5-121. Secondary Fluid Temperature (STC-34): Test No. 8 (T-1976)

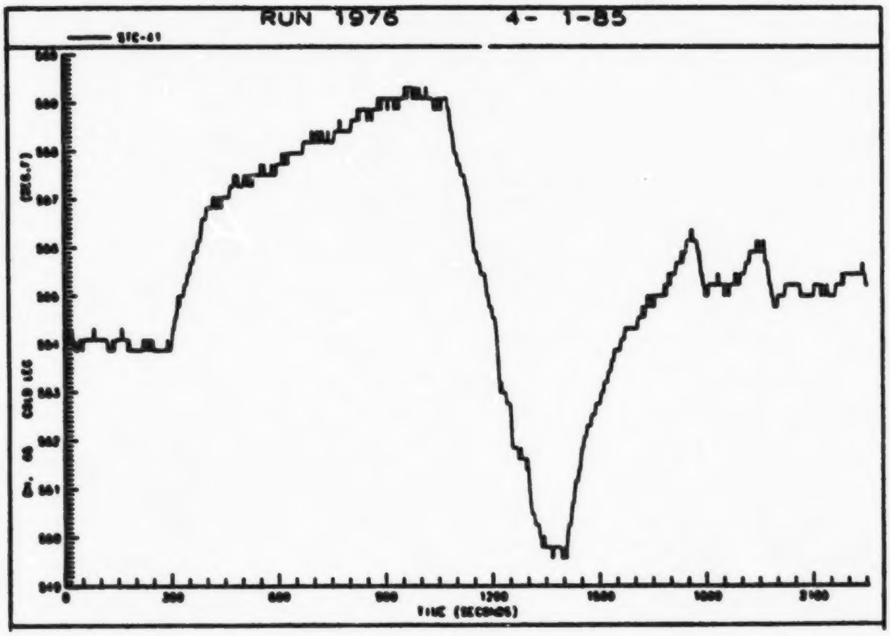

Figure 5-122. Secondary Fluid Temperature (STC-41): Test No. 8 (T-1976)

252

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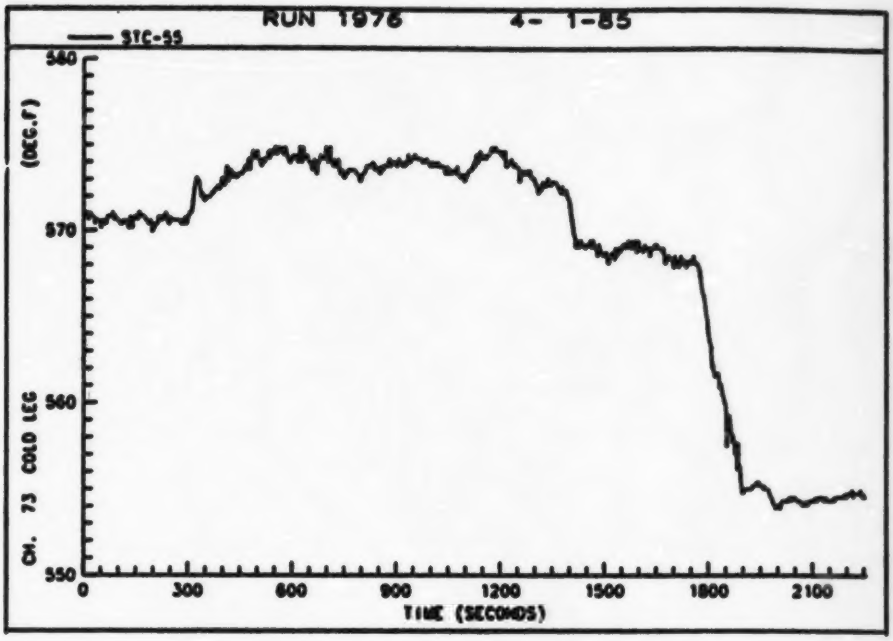

Figure 5-123. Secondary Fluid Temperature (STC-55): Test No. 8 (T-1976)

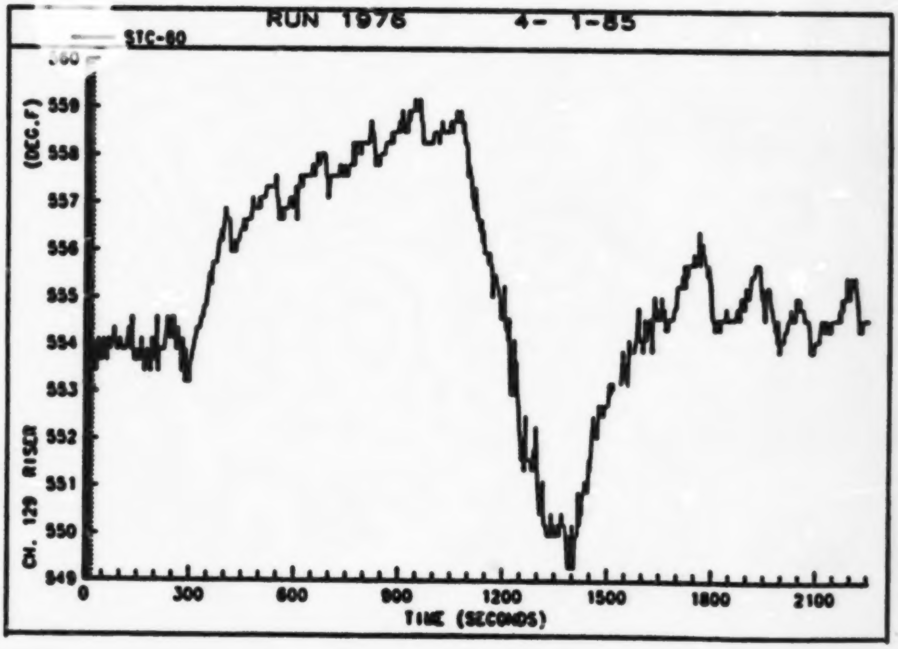

Figure 5-124. Secondary Fluid Temperature (STC-60): Test No. 8 (T-1976)

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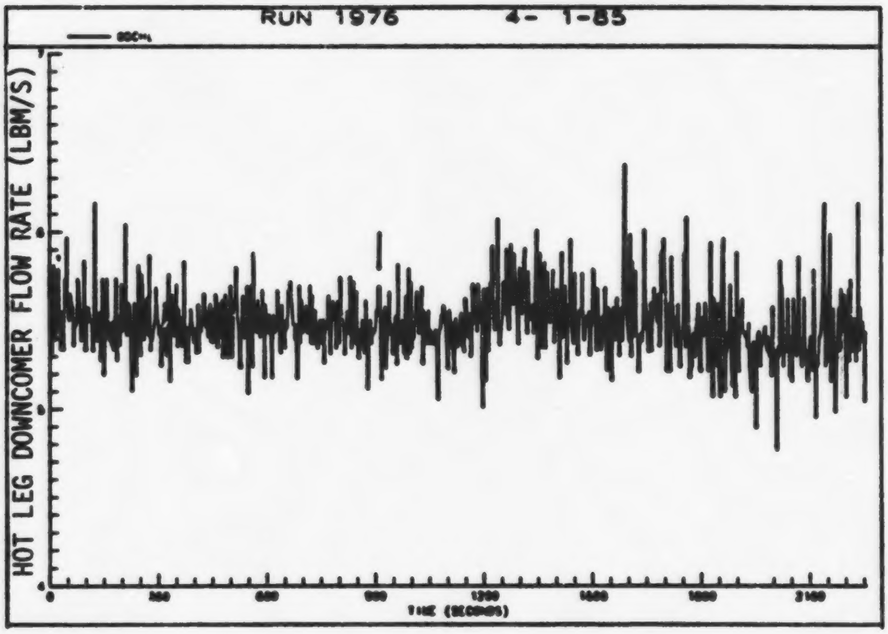

Figure 5-125. Hot Leg Downcomer Flow Rate (WDCHL): Test No. 8 (T-1976)

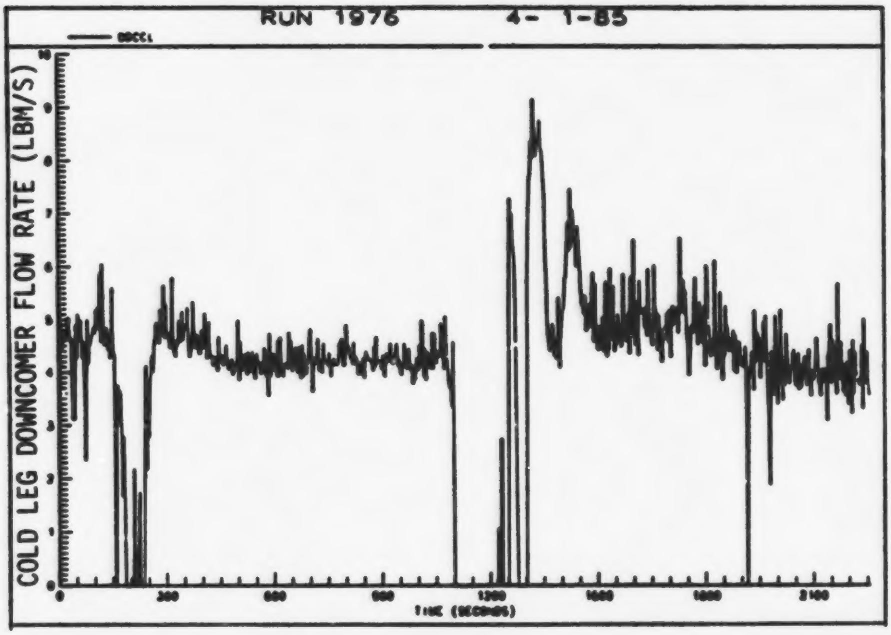

Figure 5-126. Cold Leg Downcomer Flow Rate (WDCCL): Test No. 8 (T-1976)

254

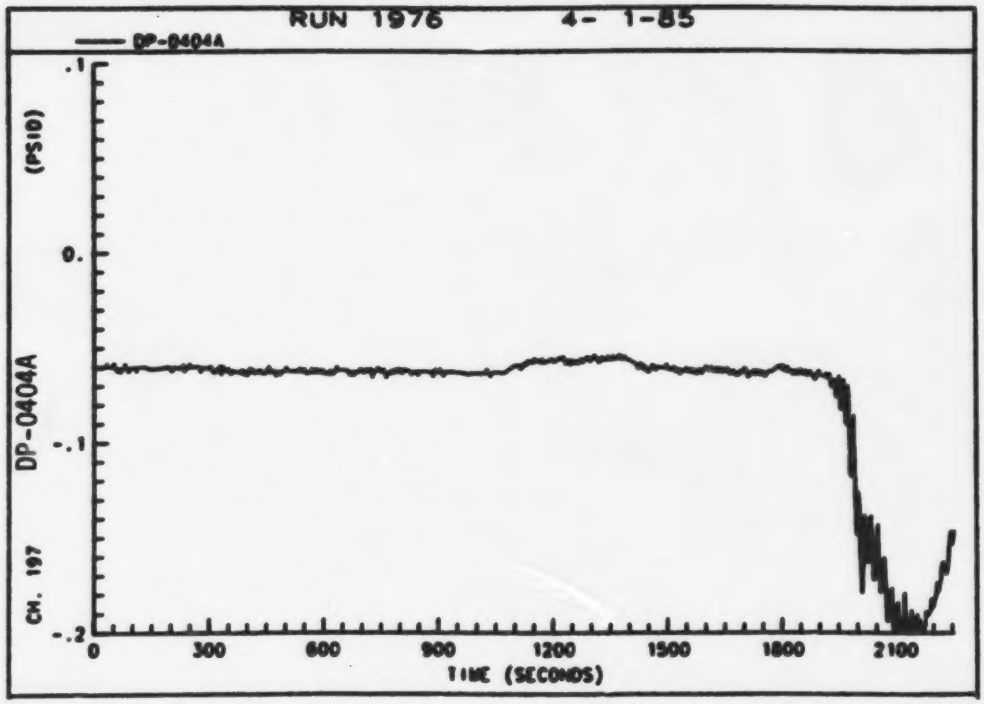

Figure 5-127. Differential Pressure, DP-0404A: Test No. 8 (T-1976)

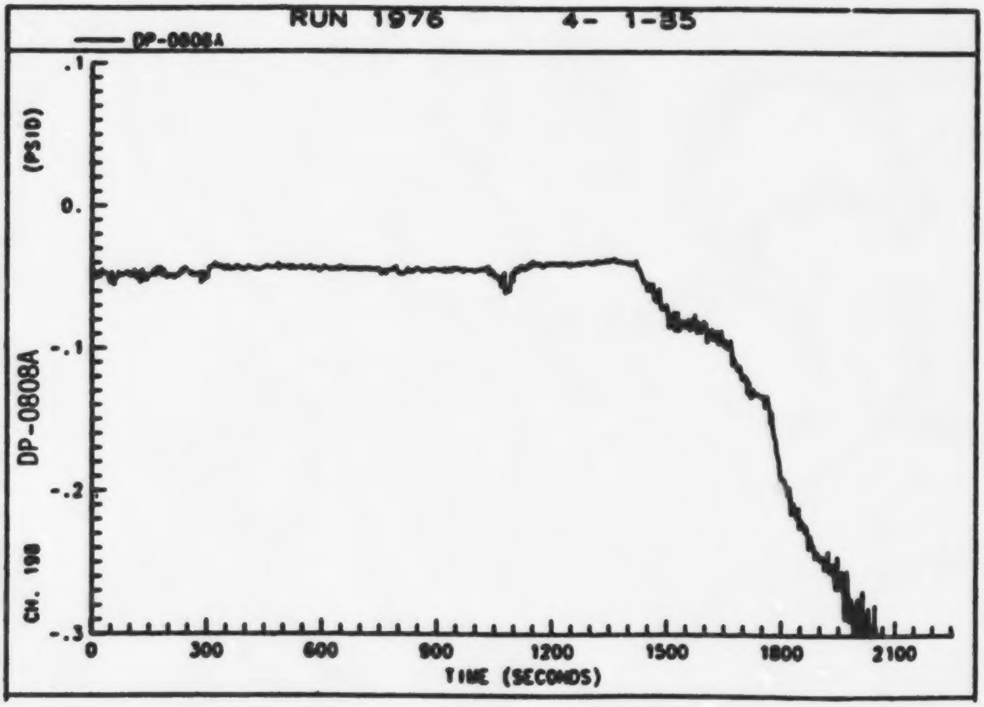

Figure 5-128. Differential Pressure, DP-0808A: Test No. 8 (T-1976)

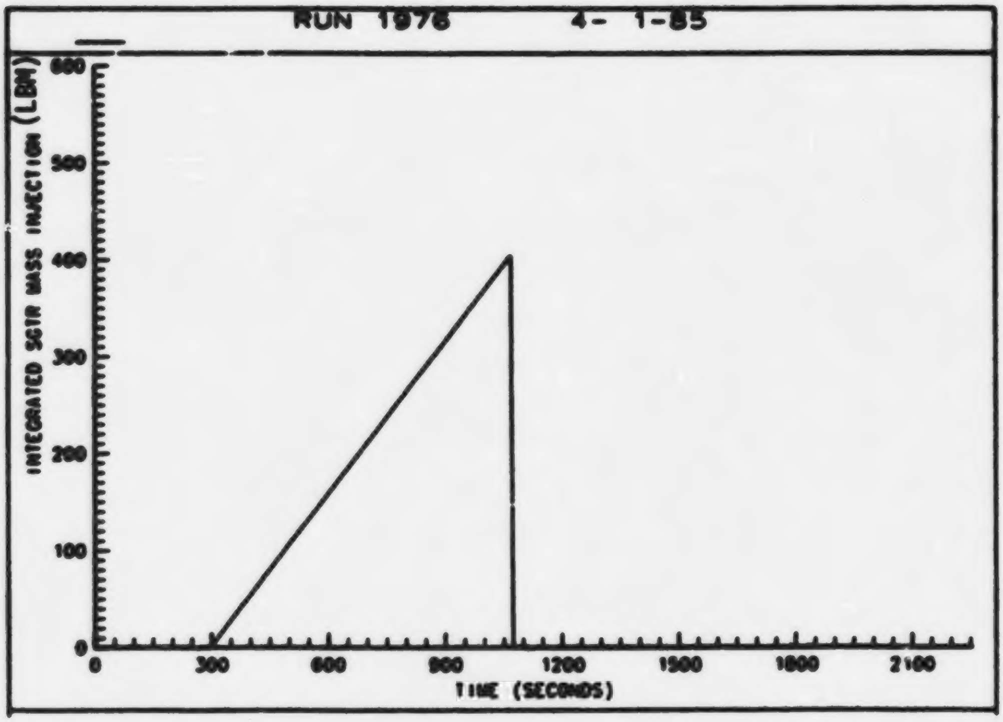

Figure 5-129. Integrated SGTR Flow: Test No. 8 (T-1976)

256

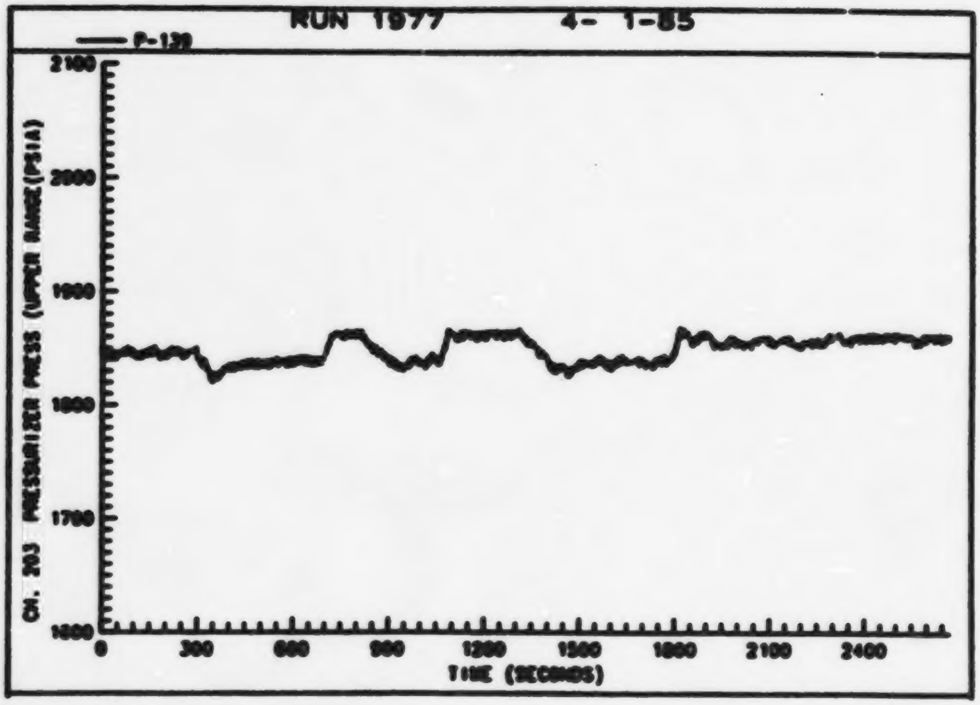

Figure 5-130. Primary System (Pressurizer) Pressure (P-139): Test No. 8 (T-1977)

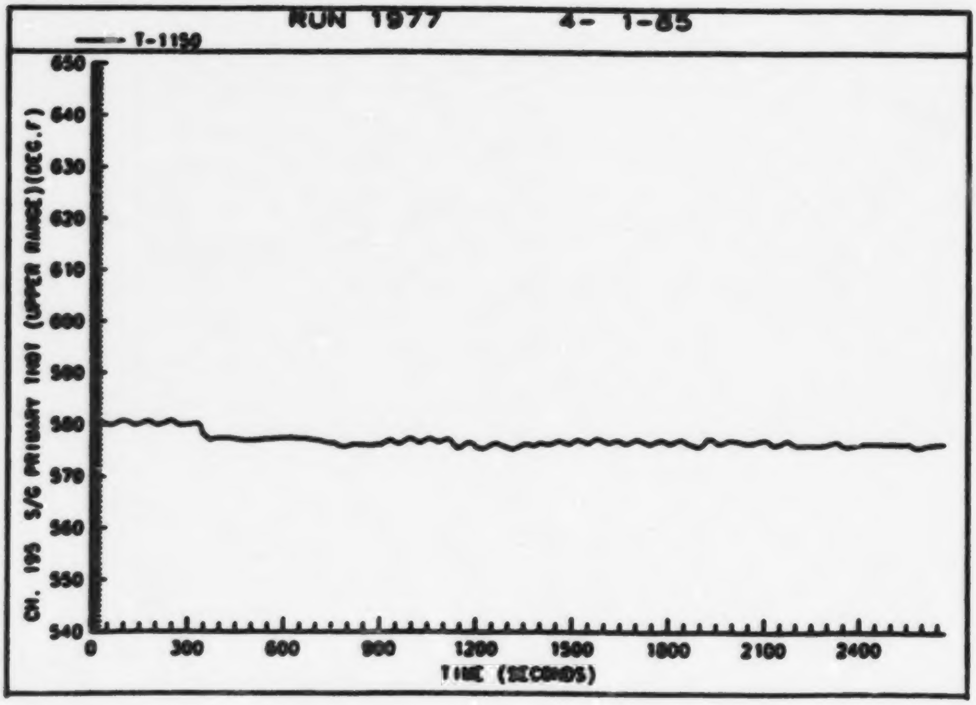

Figure 5-131. Primary Fluid T_{hot} (T-1150): Test No. 8 (T-1977)

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257

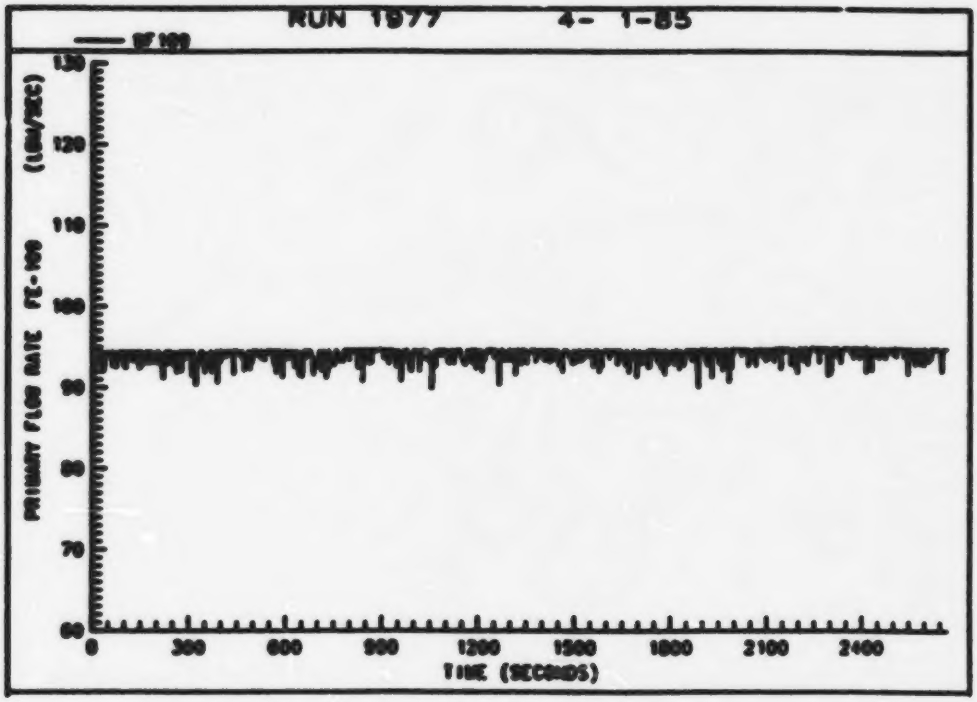

Figure 5-132. Primary Fluid Flow Rate (WF-109): Test No. 8 (T-1977)

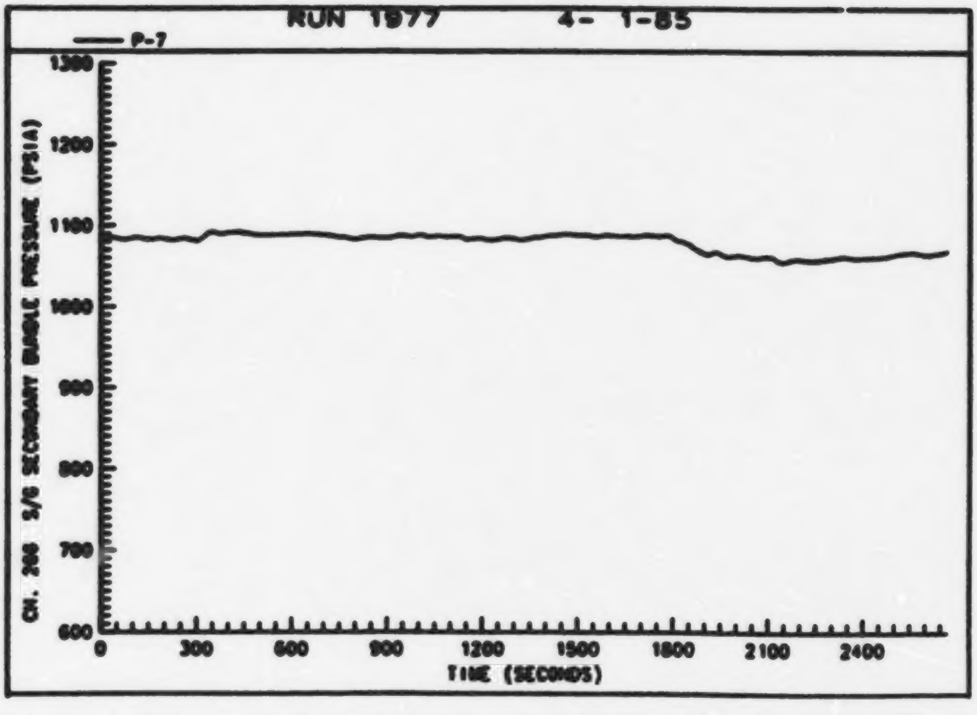

Figure 5-133. Secondary Side Pressure (P-7): Test No. 8 (T-1977)

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258

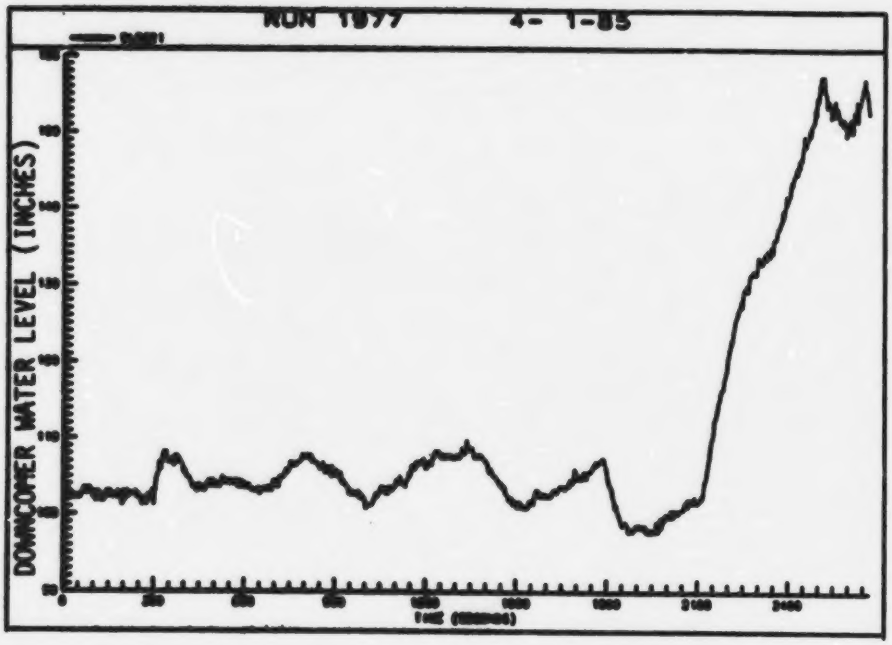

Figure 5-134. Downcomer Water Level - Wide Range (WL-9321): Test No. 8 (T-1977)

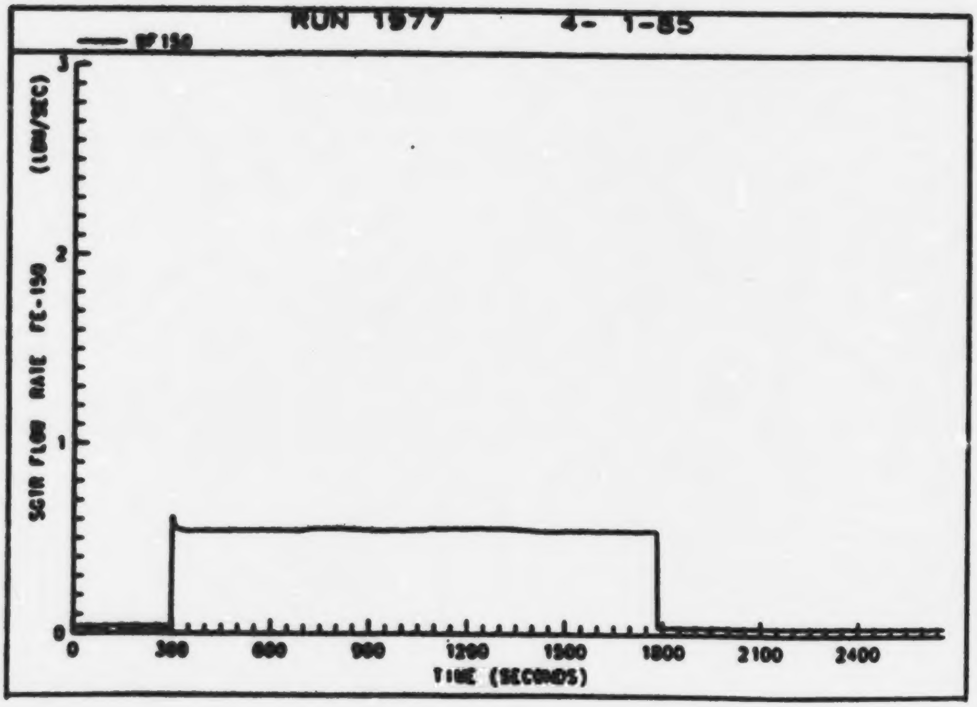

Figure 5-135. SGTR Flow Rate (WF-150): Test No. 8 (T-1977)

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259

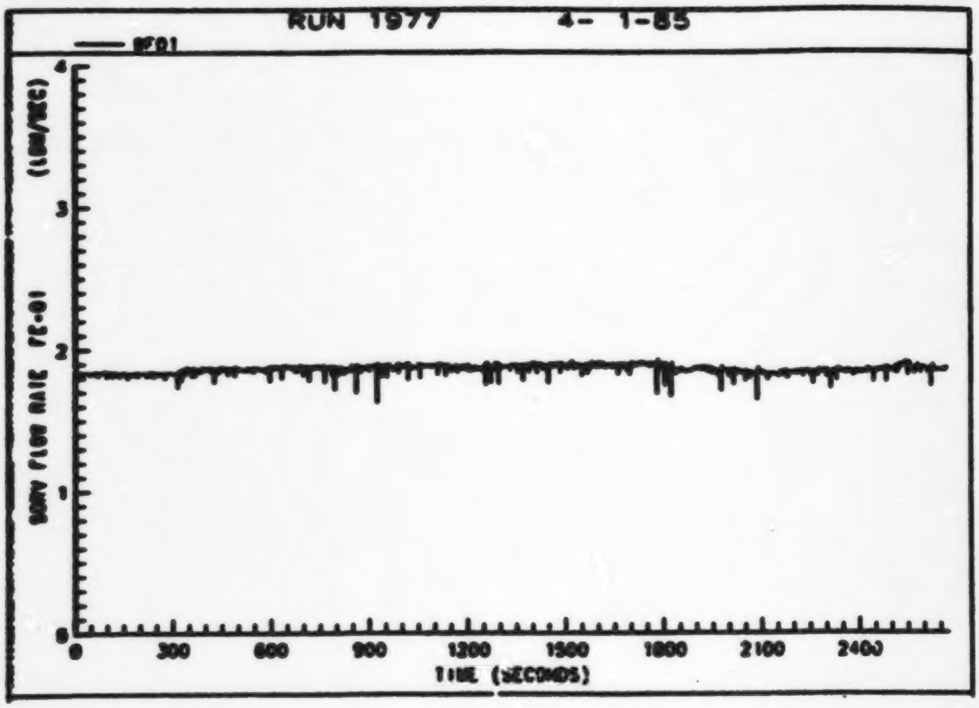

Figure 5-136. SORV Flow Rate (WF-01): Test No. 8 (T-1977)

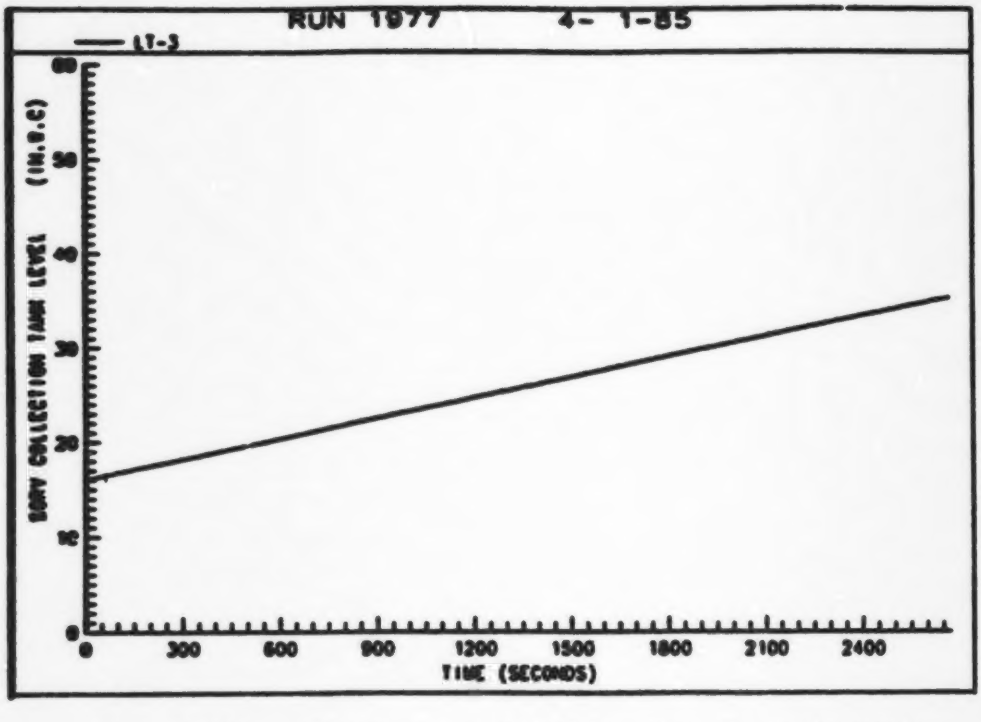

Figure 5-137. SORV Tank Level (LT-3): Test No. 8 (T-1977)

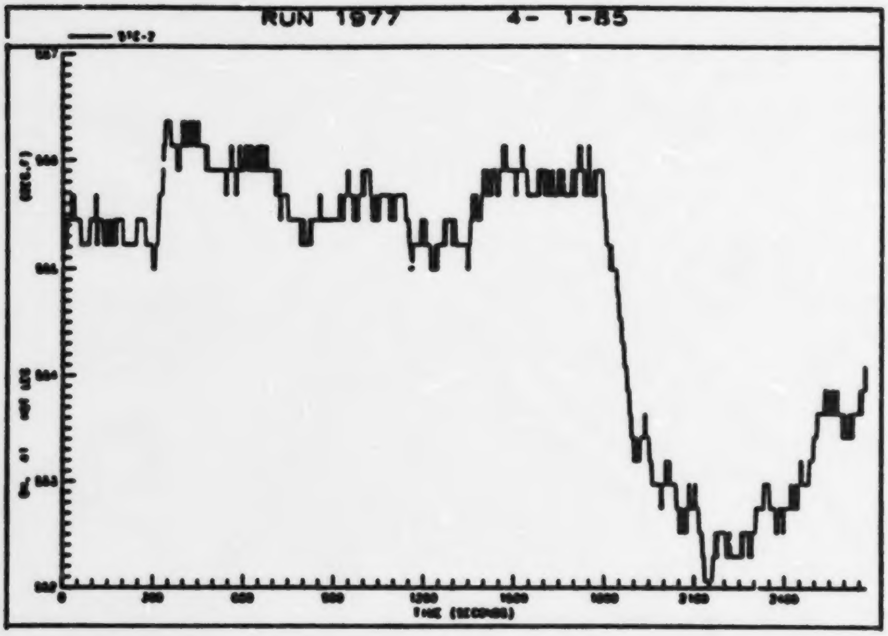

Figure 5-138. Secondary Fluid Temperature (STC-2): Test No. 8 (T-1977)

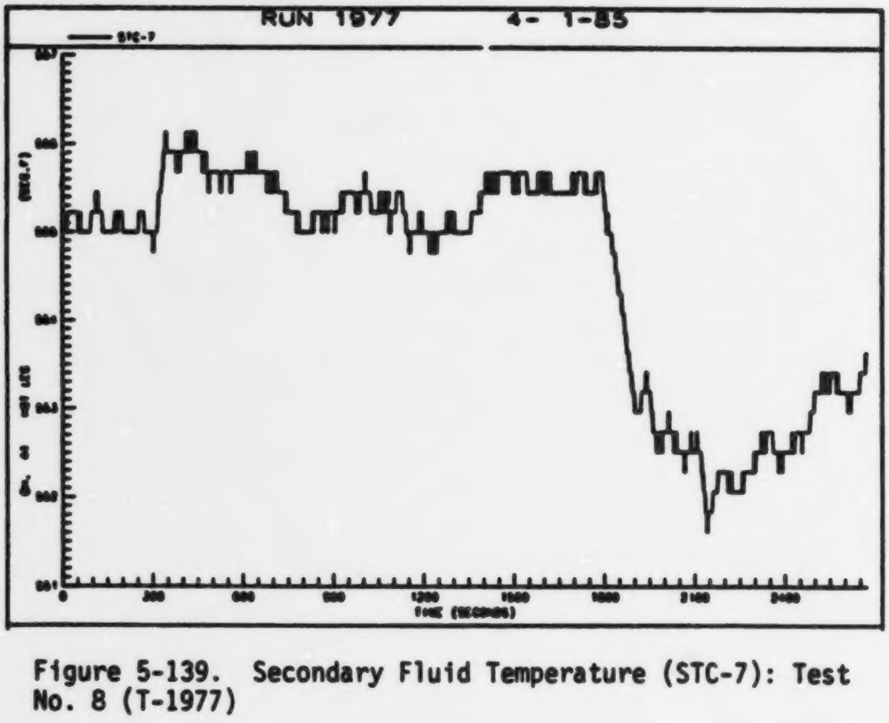

Figure 5-139. Secondary Fluid Temperature (STC-7): Test No. 8 (T-1977)

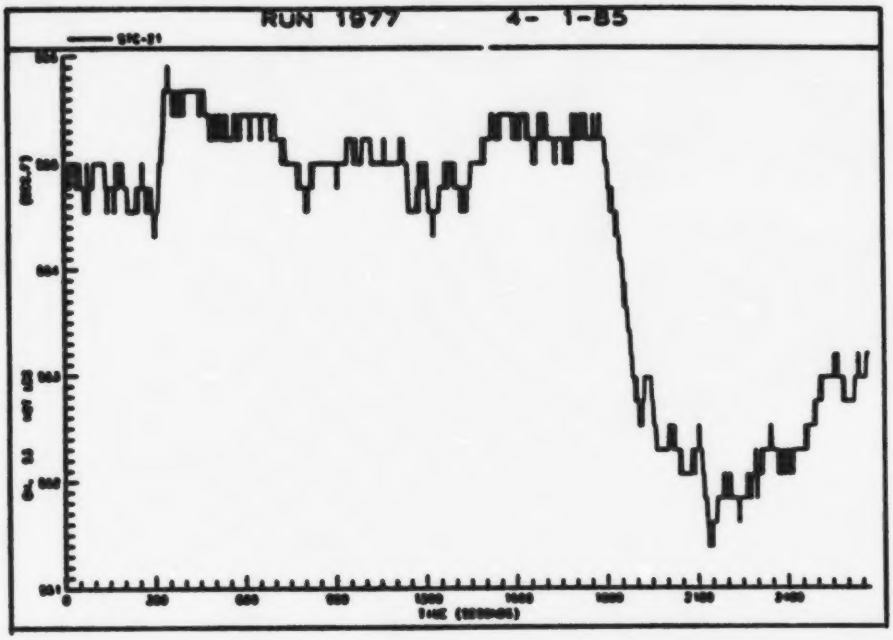

Figure 5-140. Secondary Fluid Temperature (STC-21): Test No. 8 (T-1977)

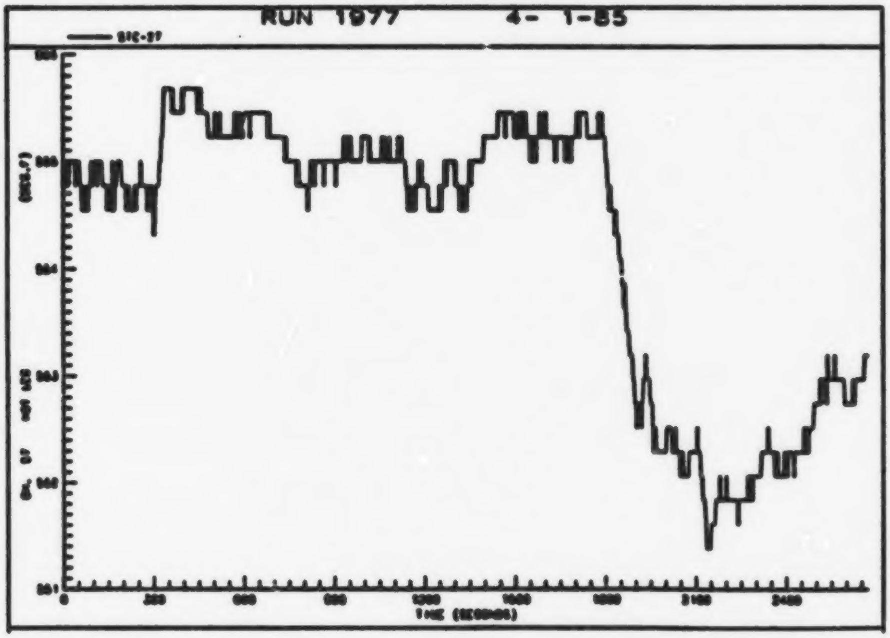

Figure 5-141. Secondary Fluid Temperature (STC-27): Test No. 8 (T-1977)

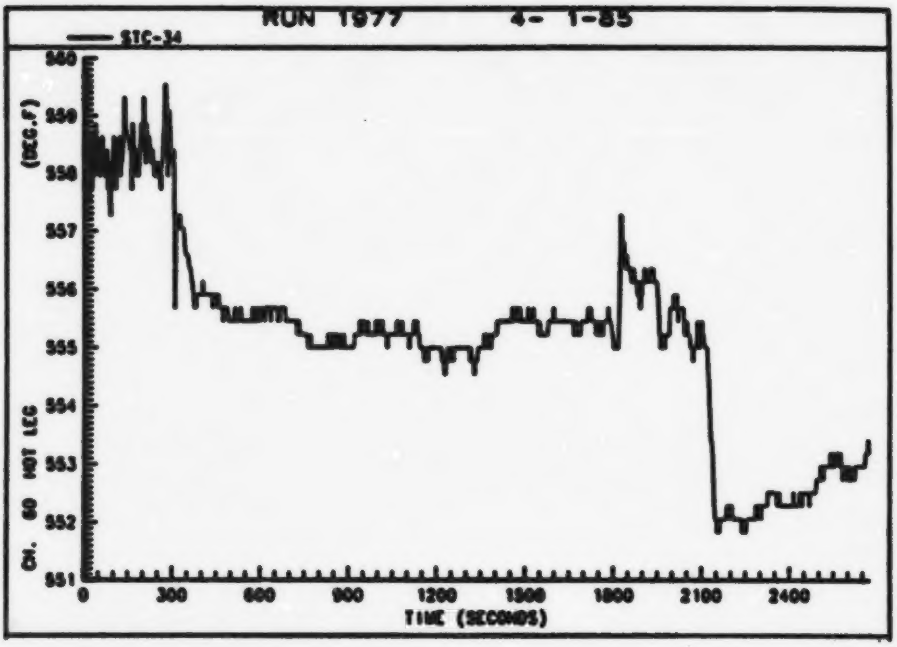

Figure 5-142. Secondary Fluid Temperature (STC-34): Test No. 8 (T-1977)

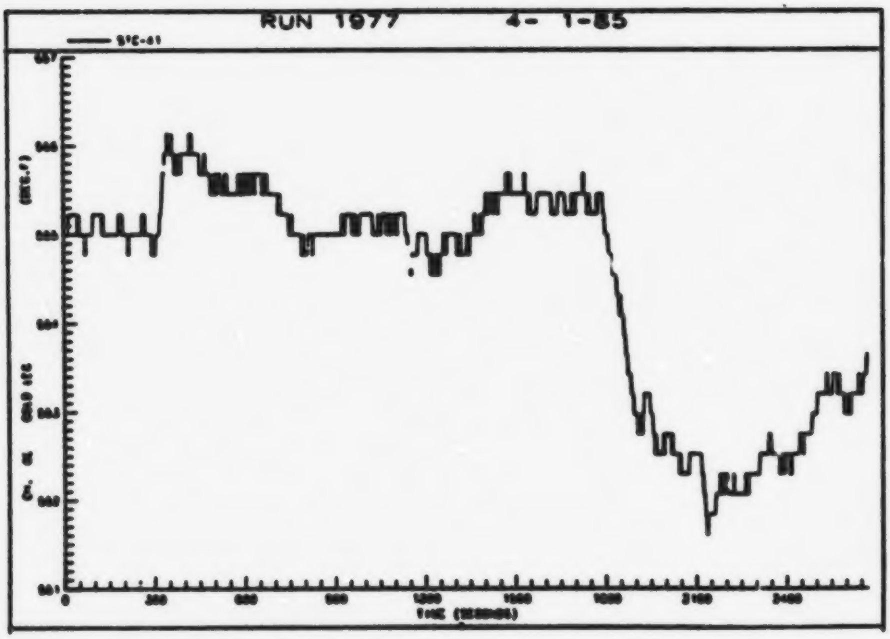

Figure 5-143. Secondary Fluid Temperature (STC-41): Test No. 8 (T-1977)

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263

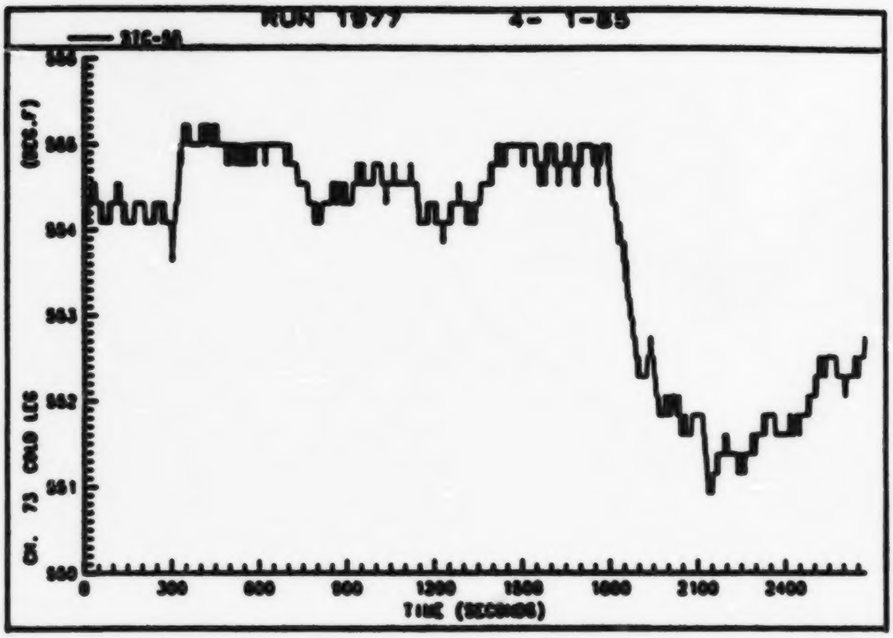

Figure 5-144. Secondary Fluid Temperature (STC-55): Test No. 8 (T-1977)

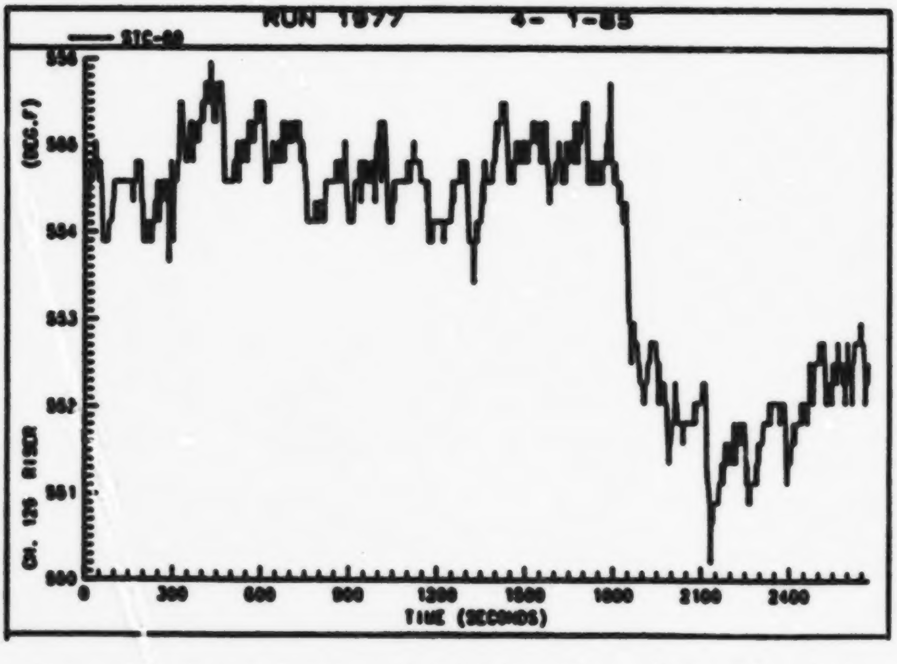

Figure 5-145. Secondary Fluid Temperature (STC-60): Test No. 8 (T-1977)

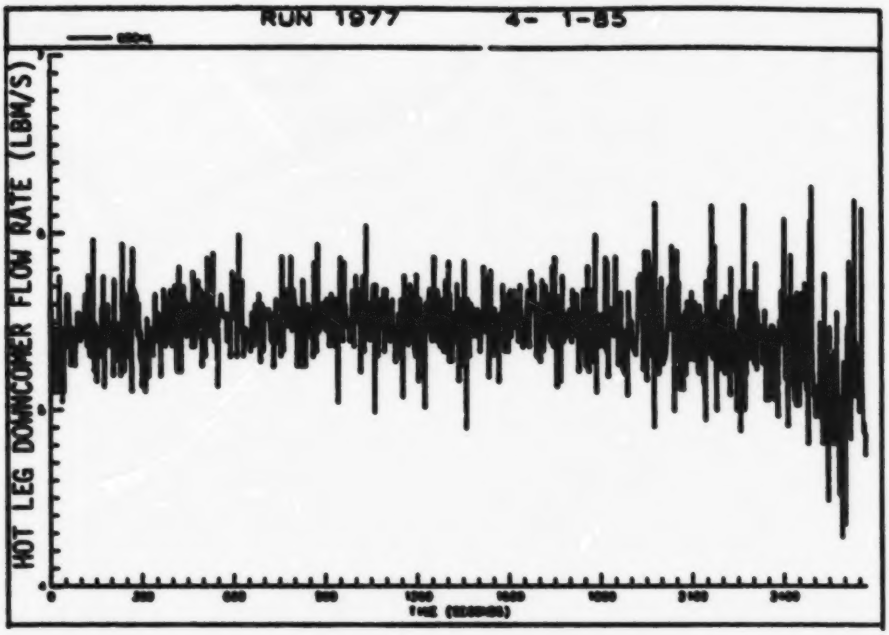

Figure 5-146. Hot Leg Downcomer Flow Rate (WDCHL): Test No. 8 (T-1977)

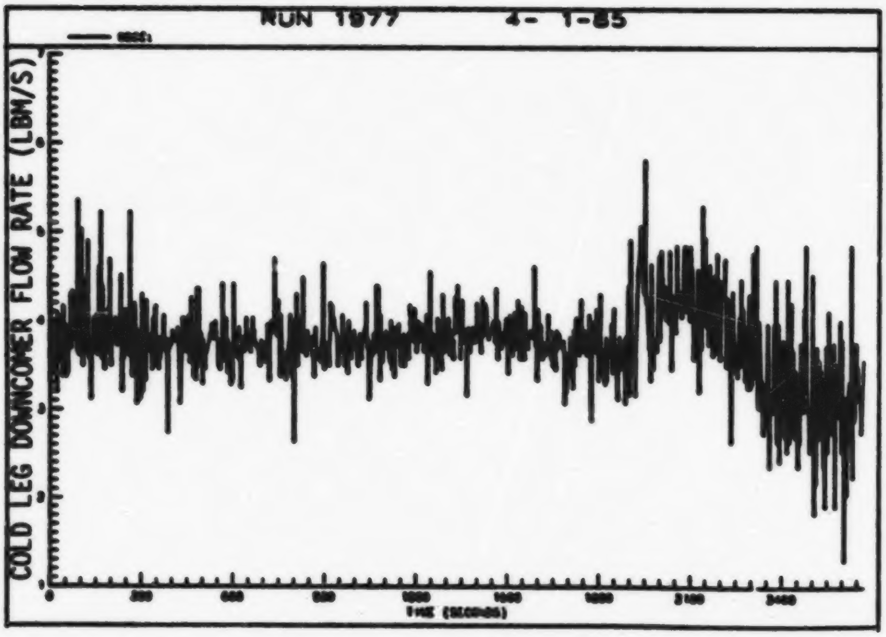

Figure 5-147. Cold Leg Downcomer Flow Rate (WDCCL): Test No. 8 (T-1977)

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265

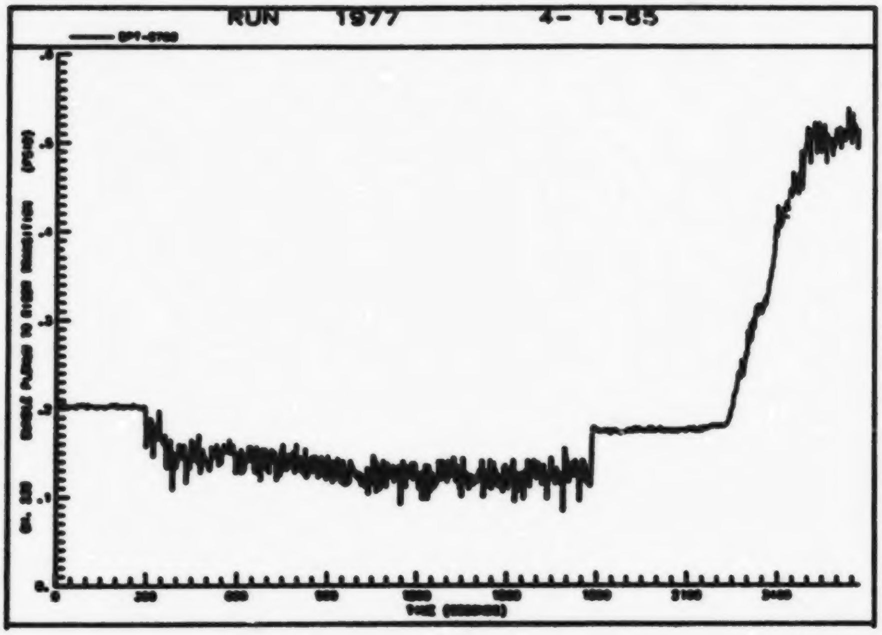

Figure 5-148. Differential Pressure DP-0760: Test No. 8 (T-1977)

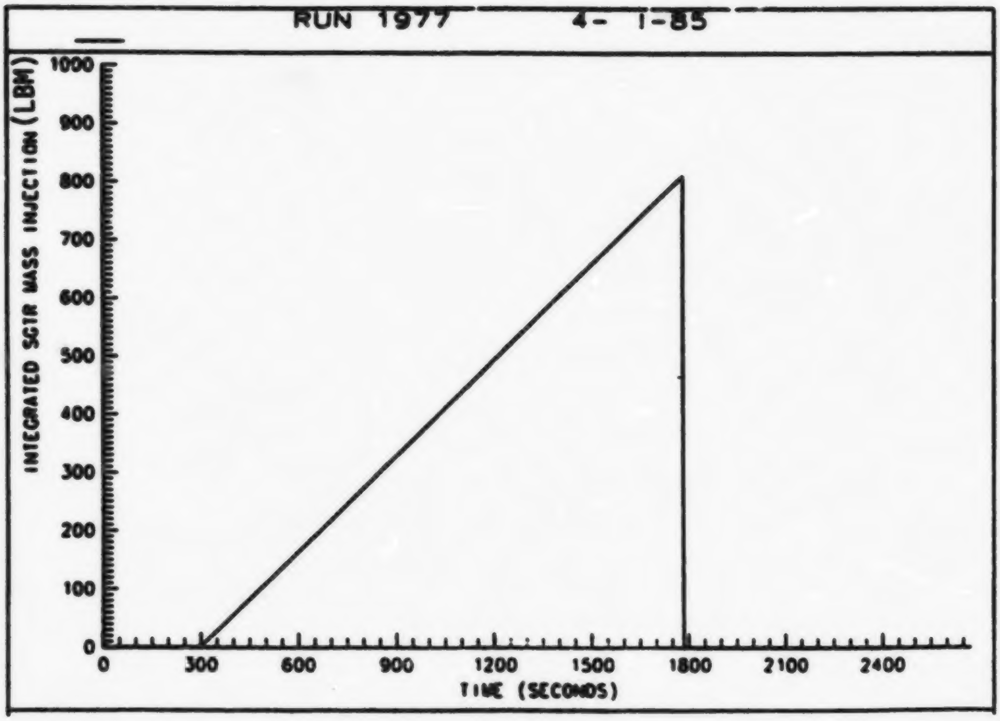

Figure 5-149. Integrated SGTR Flow: Test No. 8 (T-1977)

266

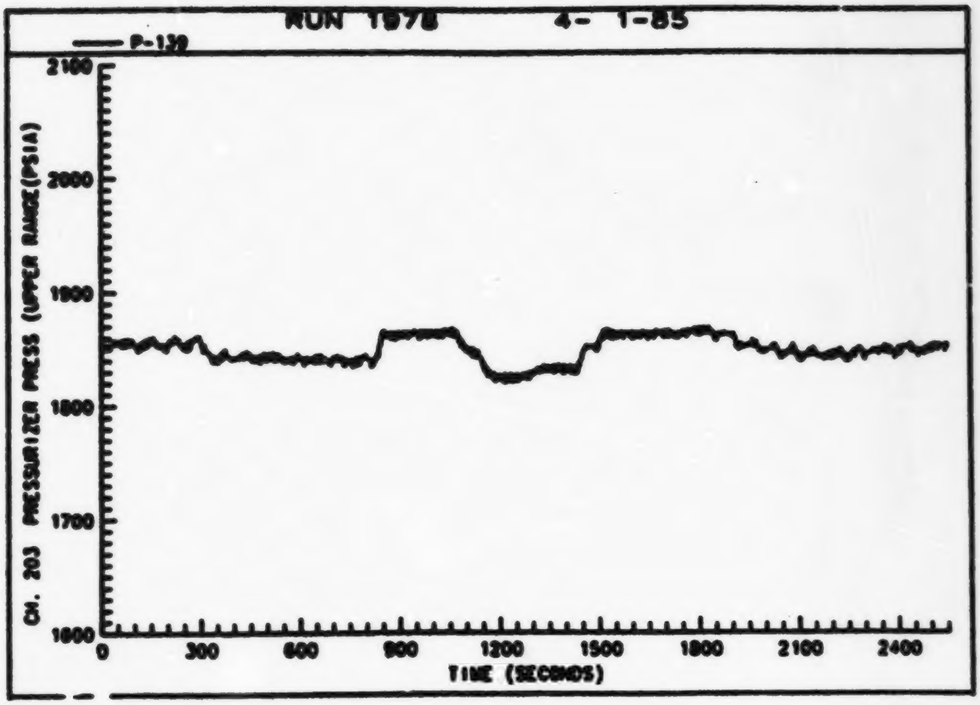

Figure 5-150. Primary System (Pressurizer) Pressure (P-139): Test No. 8 (T-1978)

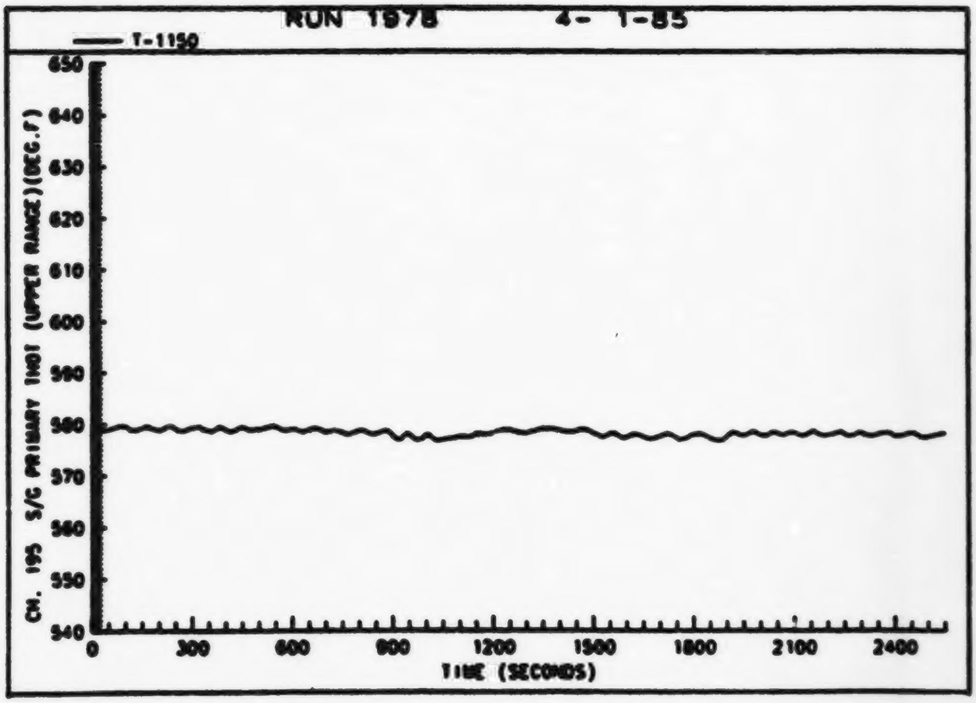

Figure 5-151. Primary Fluid T_{hot} (T-1150): Test No. 8 (T-1978)

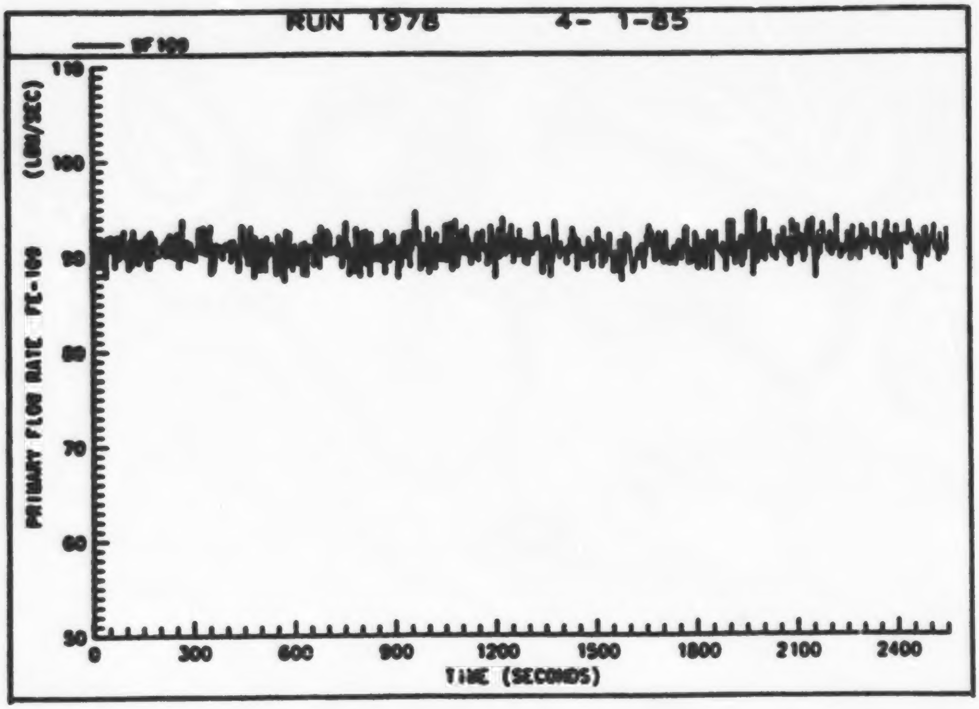

Figure 5-152. Primary Fluid Flow Rate (WF-109): Test No. 8 (T-1978)

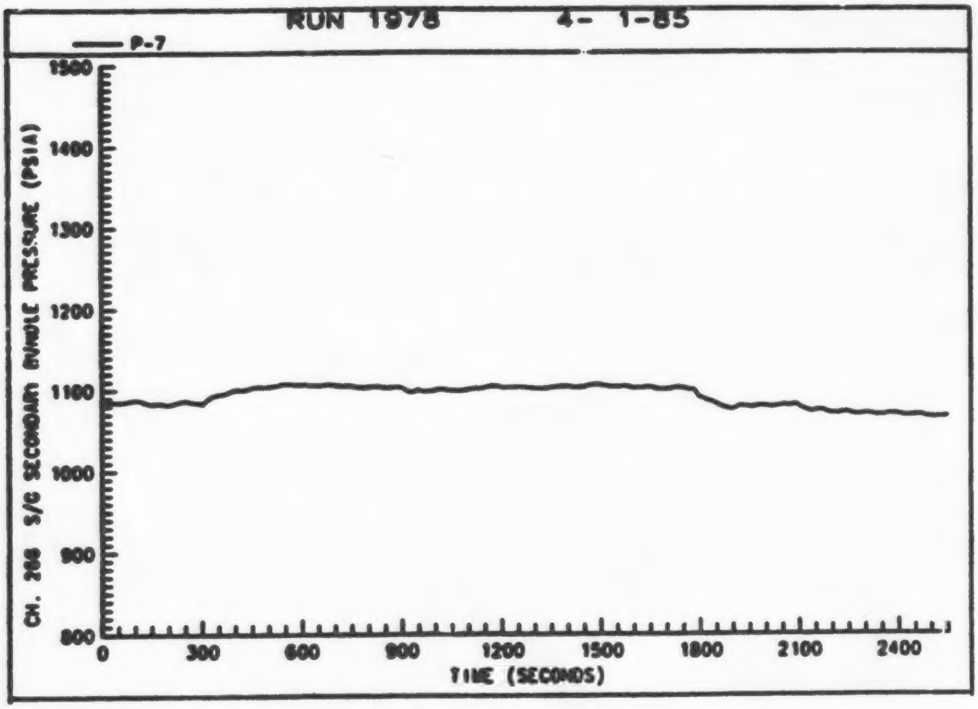

Figure 5-153. Secondary Side Pressure (P-7): Test No. 8 (T-1978)

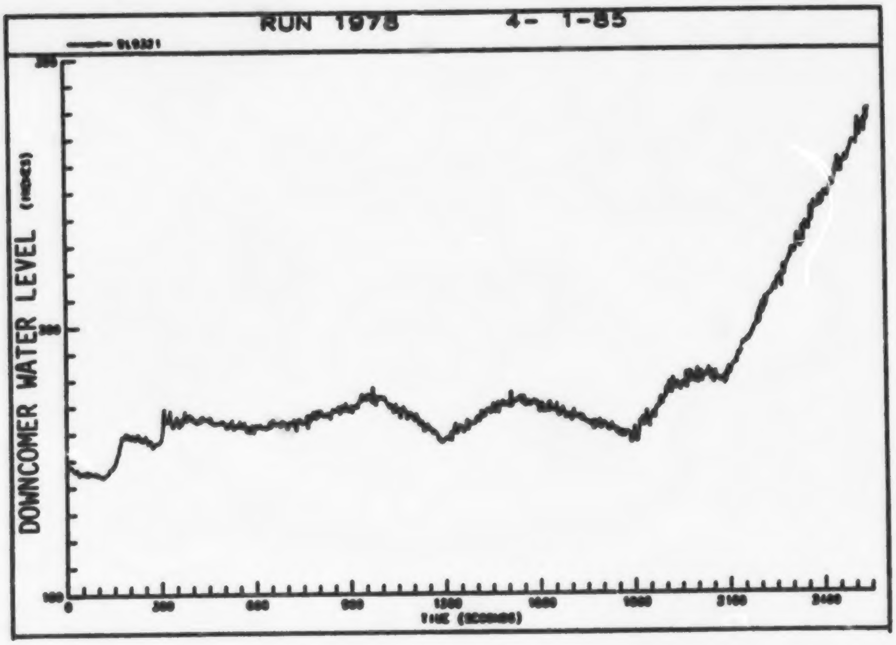

Figure 5-154. Downcomer Water Level - Wide Range (WL-9321): Test No. 8 (T-1978)

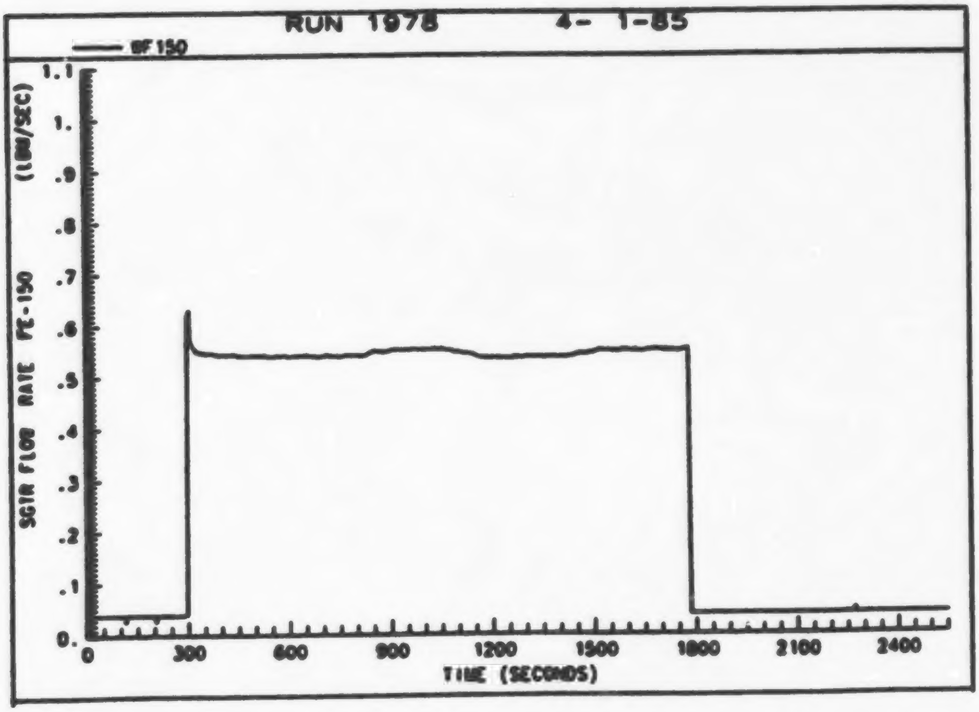

Figure 5-155. SGTR Flow Rate (WF-150): Test No. 8 (T-1978)

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269

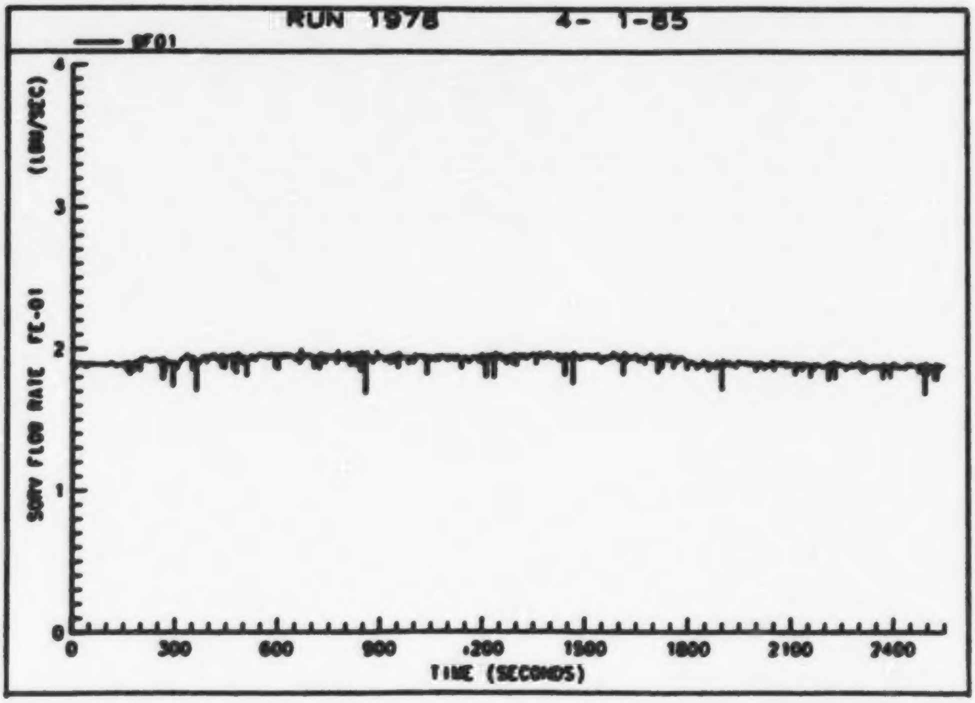

Figure 5-156. SORV Flow Rate (WF-01): Test No. 8 (T-1978)

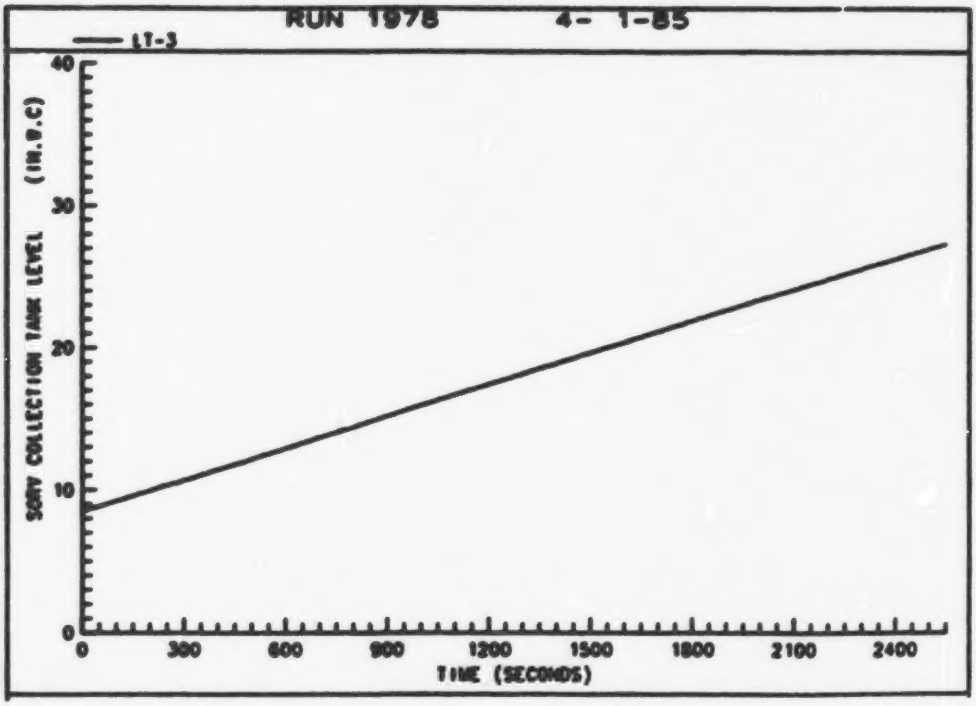

Figure 5-157. SORV Tank Level (LT-3): Test No. 8 (T-1978)

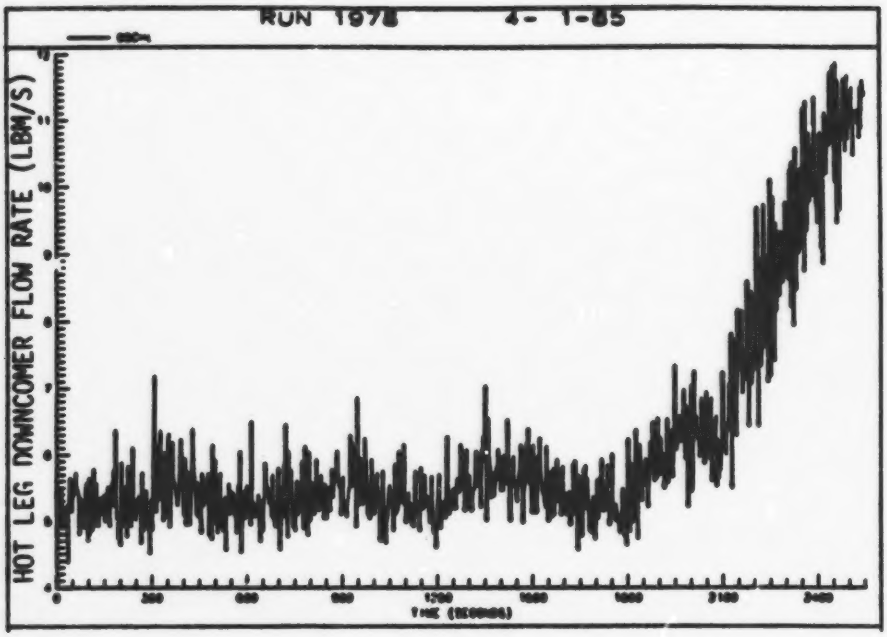

Figure 5-158. Hot Leg Downcomer Flow Rate (WDCHL): Test No. 8 (T-1978)

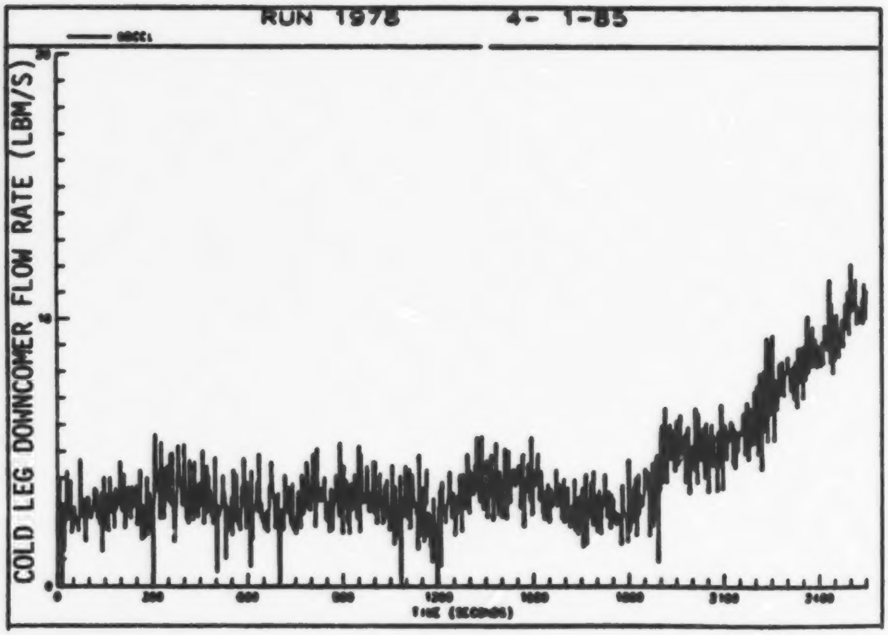

Figure 5-159. Cold Leg Downcomer Flow Rate (WDCCL): Test No. 8 (T-1978)

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271

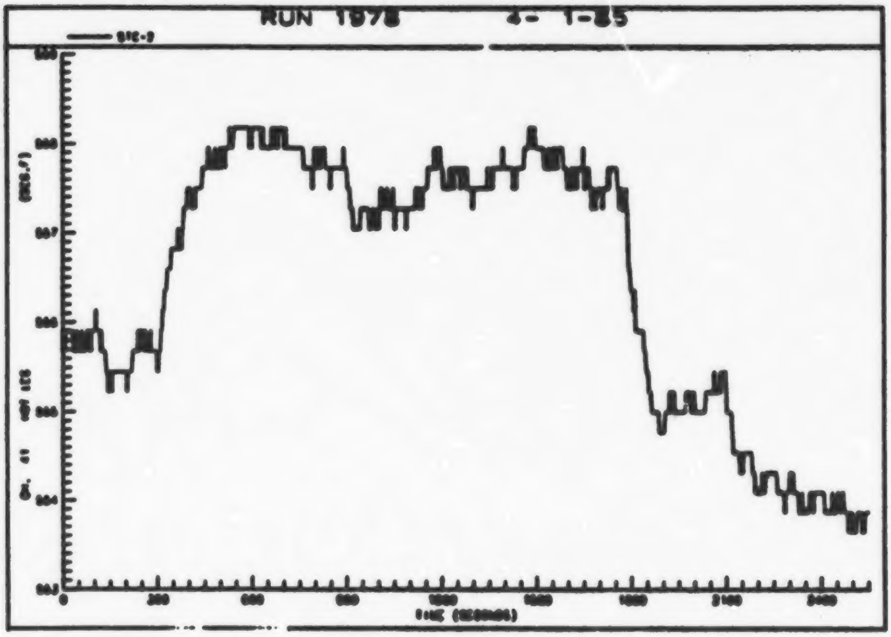

Figure 5-160. Secondary Fluid Temperature (STC-2): Test No. 8 (T-1978)

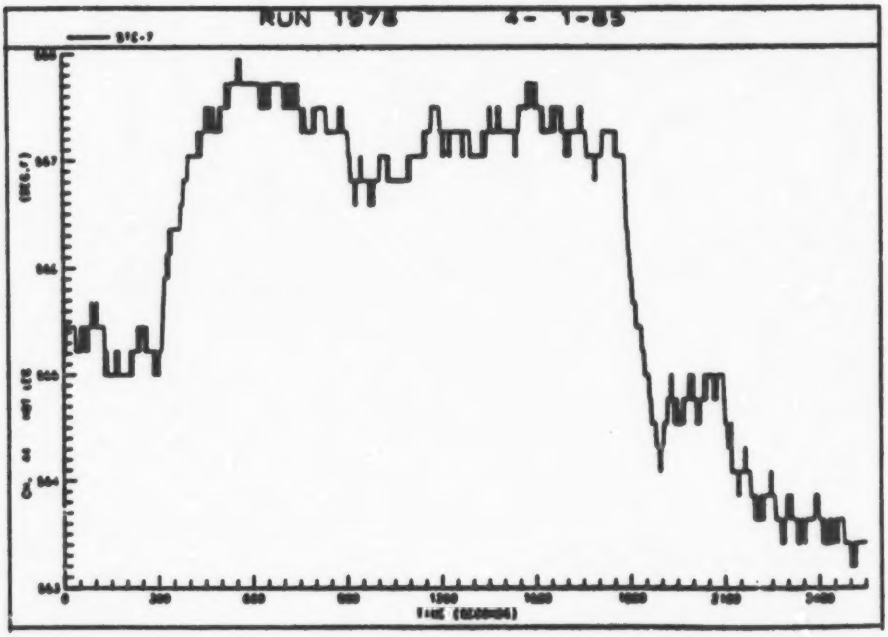

Figure 5-161. Secondary Fluid Temperature (STC-7): Test No. 8 (T-1978)

272

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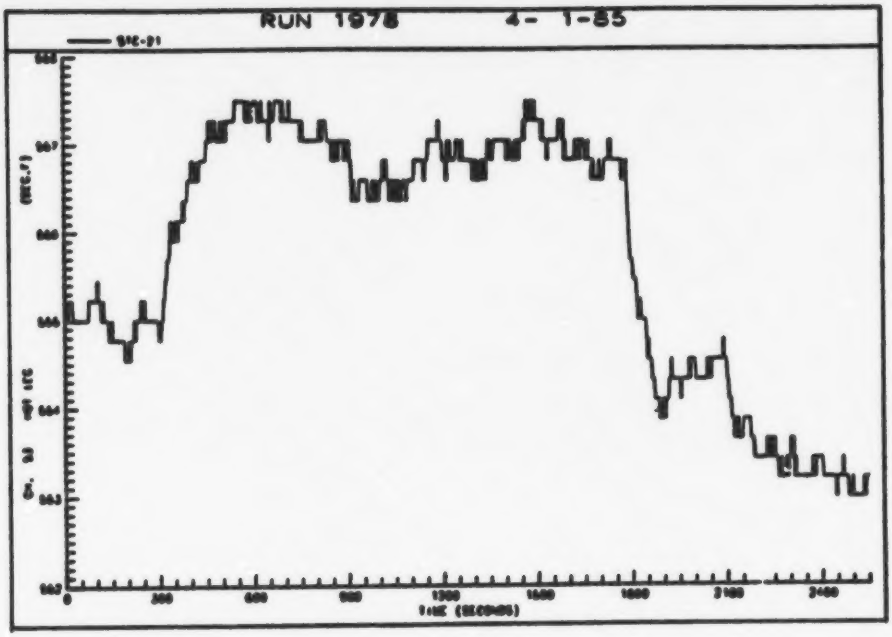

Figure 5-162. Secondary Fluid Temperature (STC-21): Test No. 8 (T-1978)

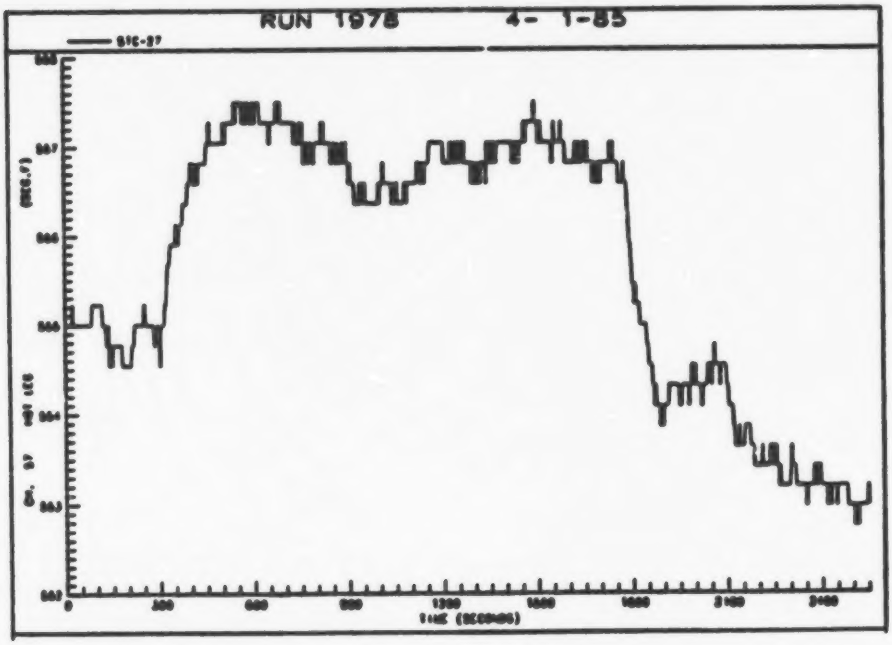

Figure 5-163. Secondary Fluid Temperature (STC-27): Test No. 8 (T-1978)

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273

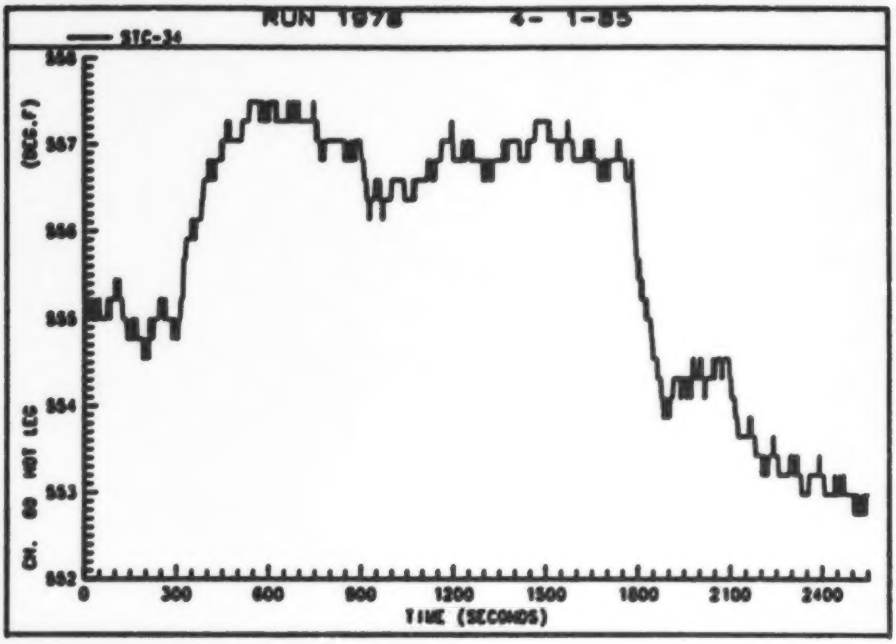

Figure 5-164. Secondary Fluid Temperature (STC-34): Test No. 8 (T-1978)

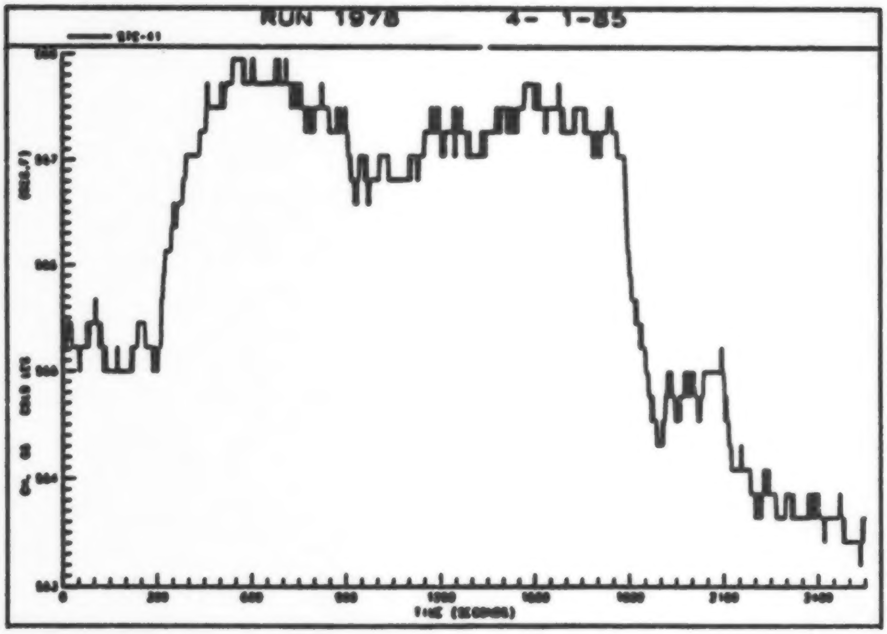

Figure 5-165. Secondary Fluid Temperature (STC-41): Test No. 8 (T-1978)

274

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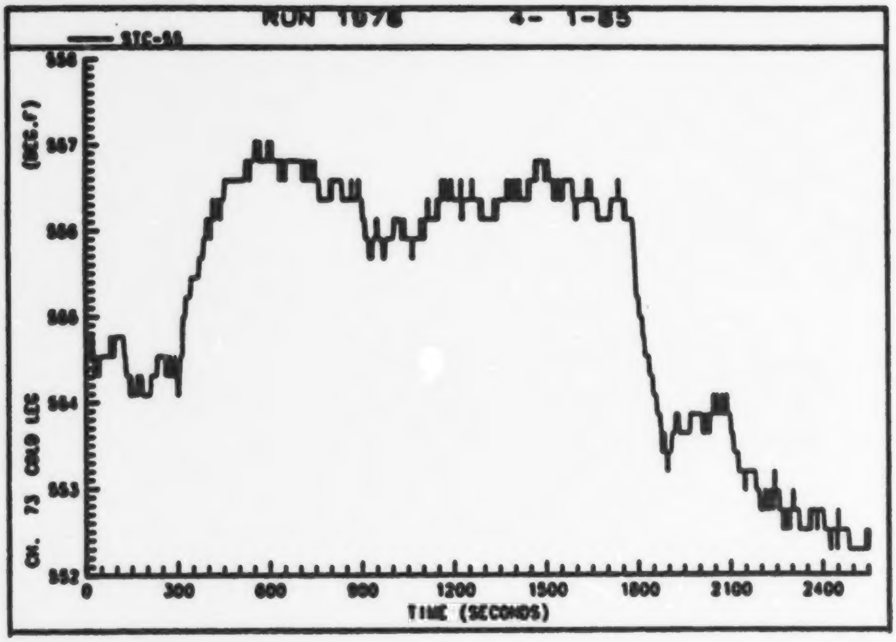

Figure 5-166. Secondary Fluid Temperature (STC-55): Test No. 8 (T-1978)

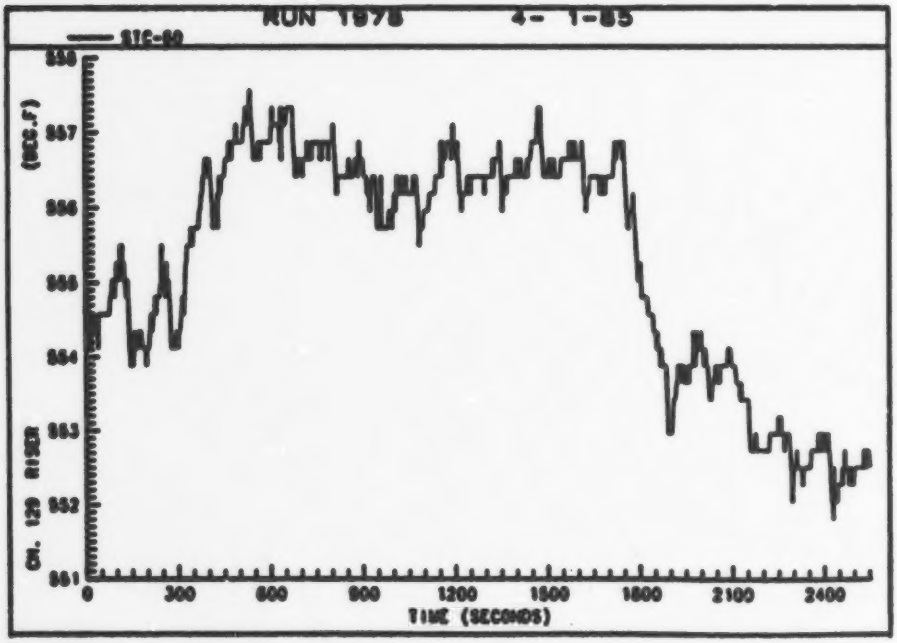

Figure 5-167. Secondary Fluid Temperature (STC-60): Test No. 8 (T-1978)

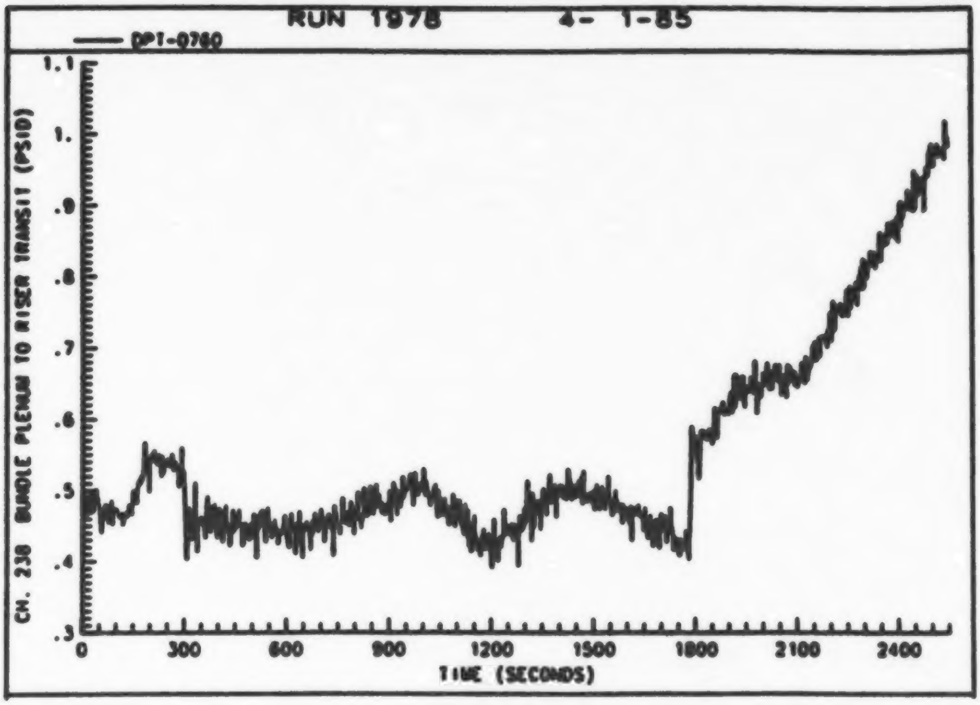

Figure 5-168. Differential Pressure DP-0760: Test No. 8 (T-1978)

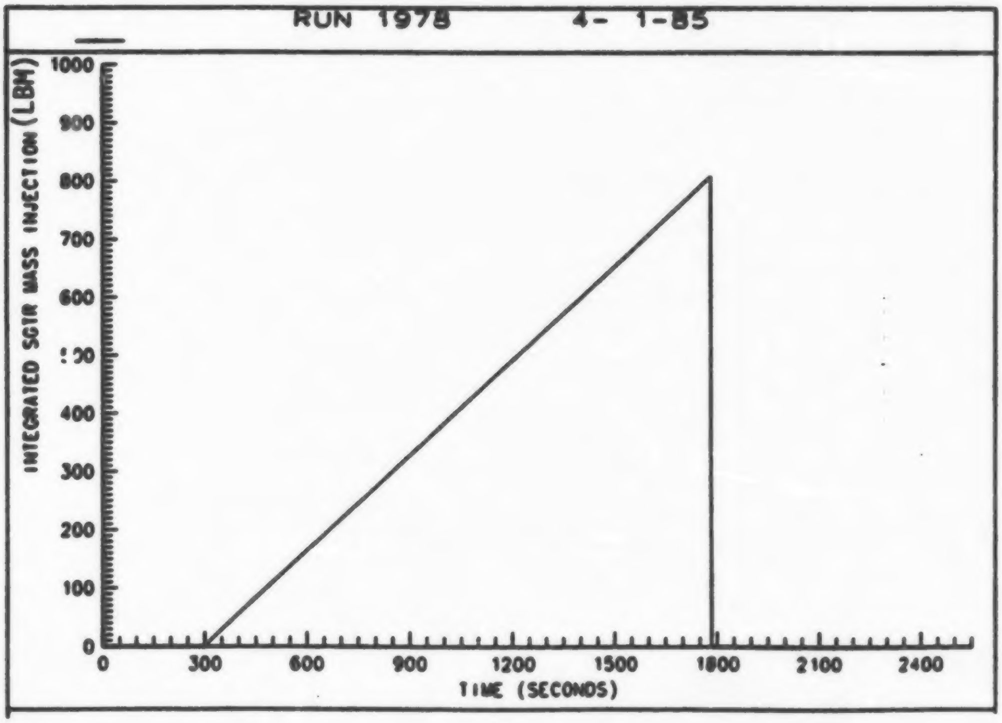

Figure 5-169. Integrated SGTR Flow: Test No. 8 (T-1978)

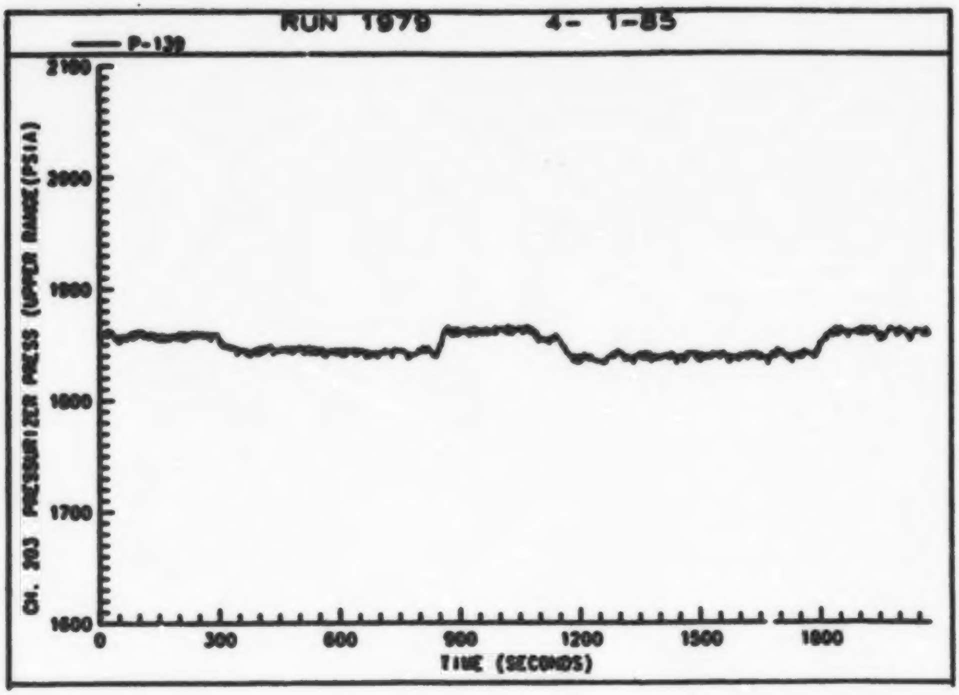

Figure 5-170. Primary System (Pressurizer) Pressure (P-139): Test No. 8 (T-1979)

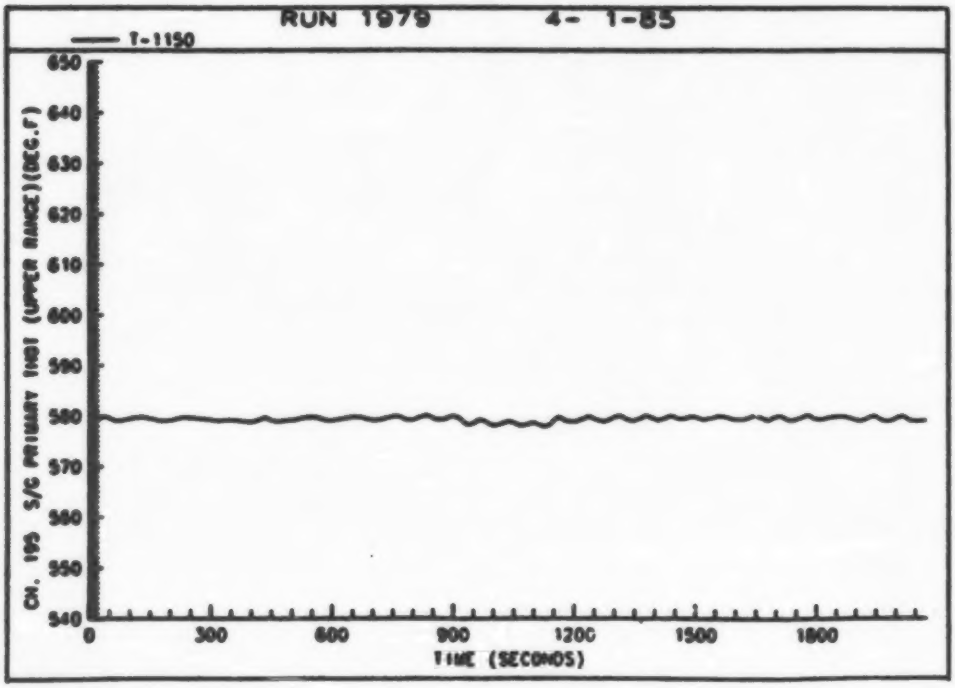

Figure 5-171. Primary Fluid T_{hot} (T-1150): Test No. 8 (T-1979)

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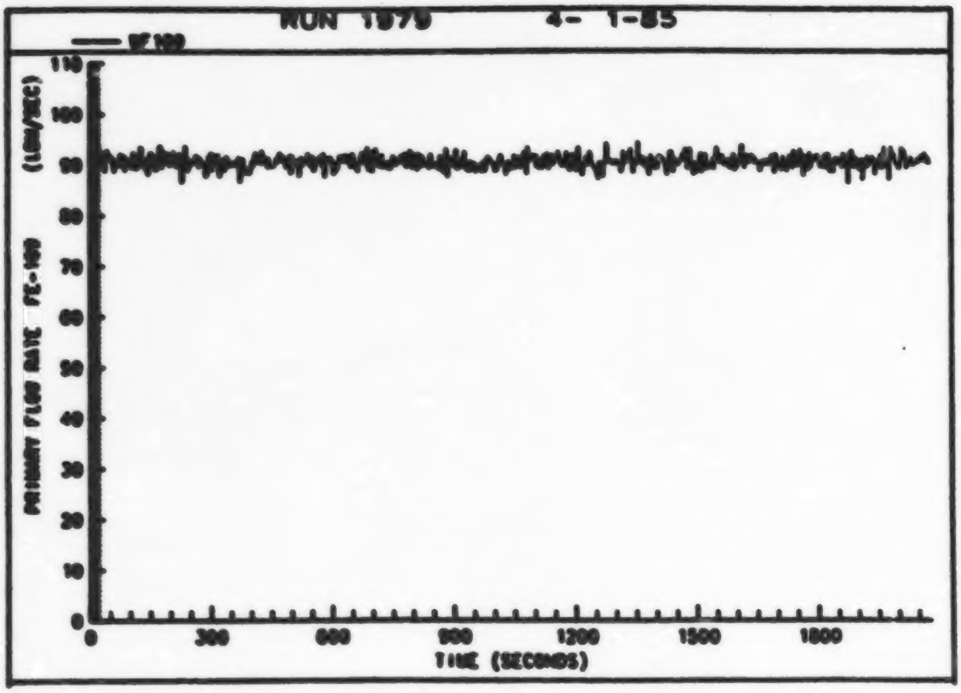

Figure 5-172. Primary Fluid Flow Rate (WF-109): Test No. 8 (T-1979)

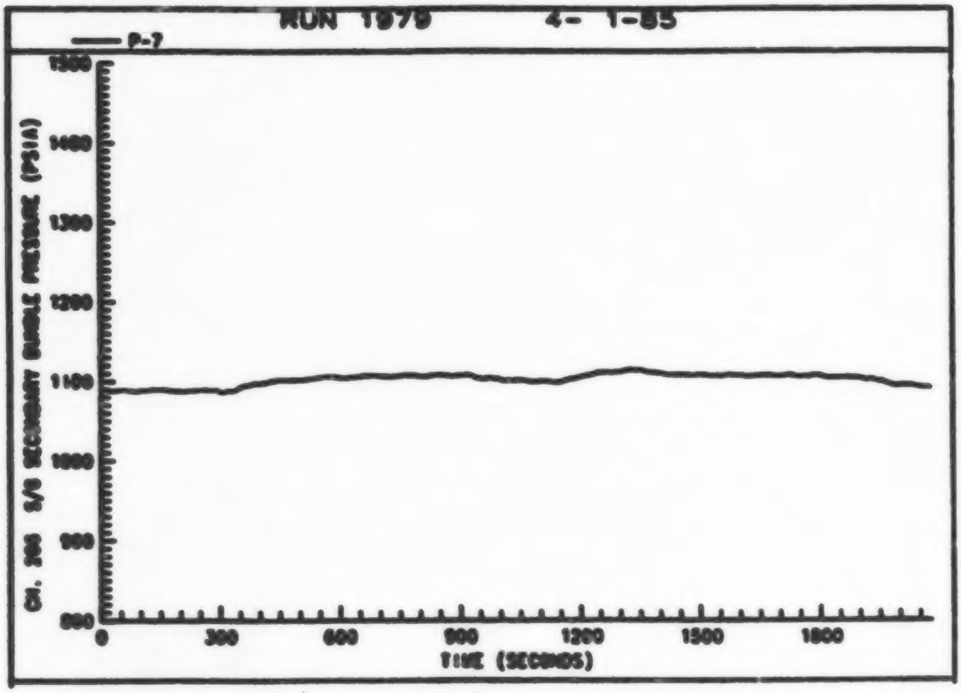

Figure 5-173. Secondary Side Pressure (P-7): Test No. 8 (T-1979)

378

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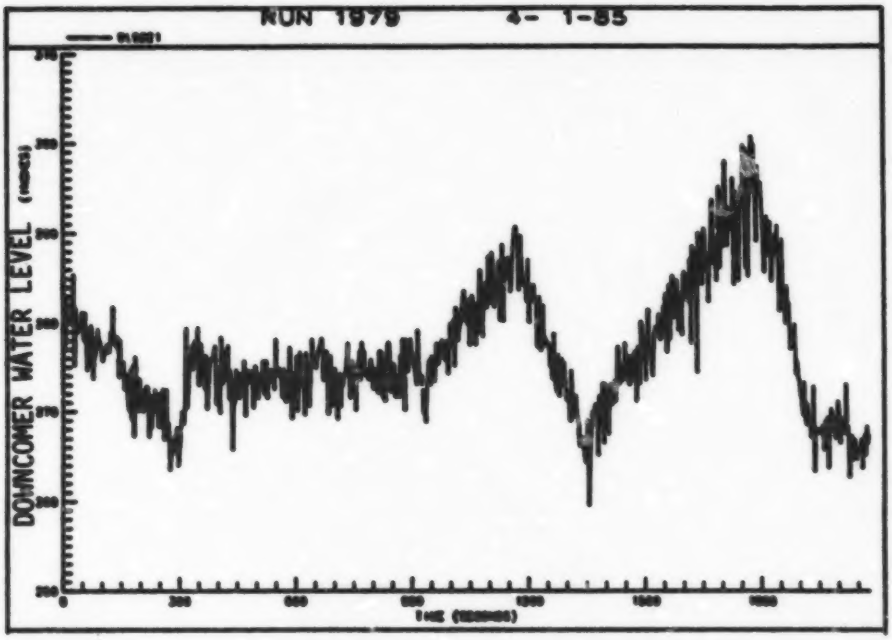

Figure 5-174. Downcomer Water Level - Wide Range (WL-9321): Test No. 8 (T-1979)

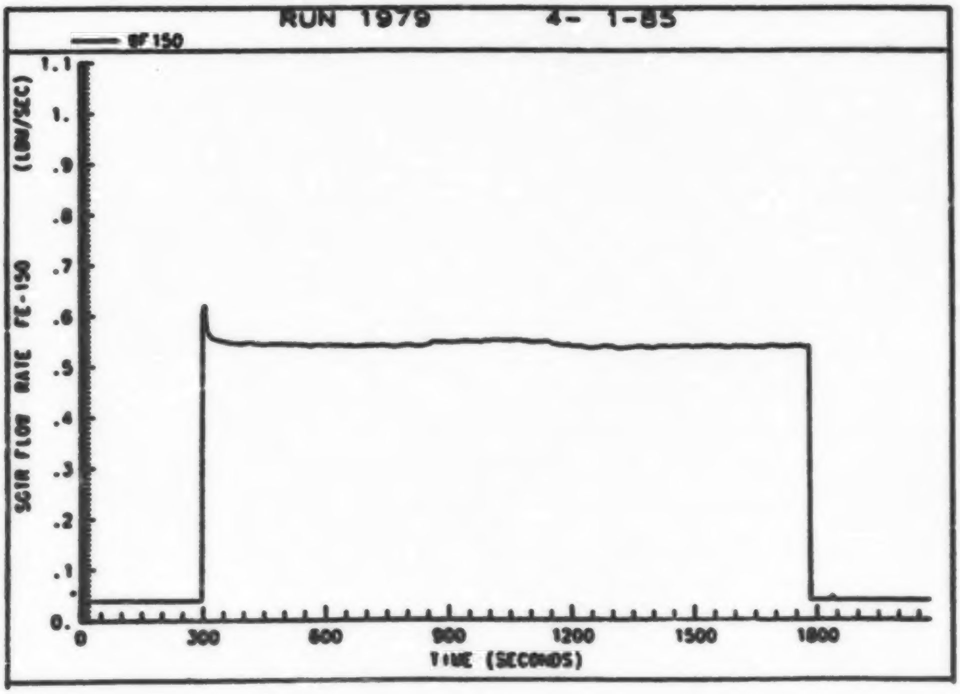

Figure 5-175. SGTR Flow Rate (WF-150): Test No. 8 (T-1979)

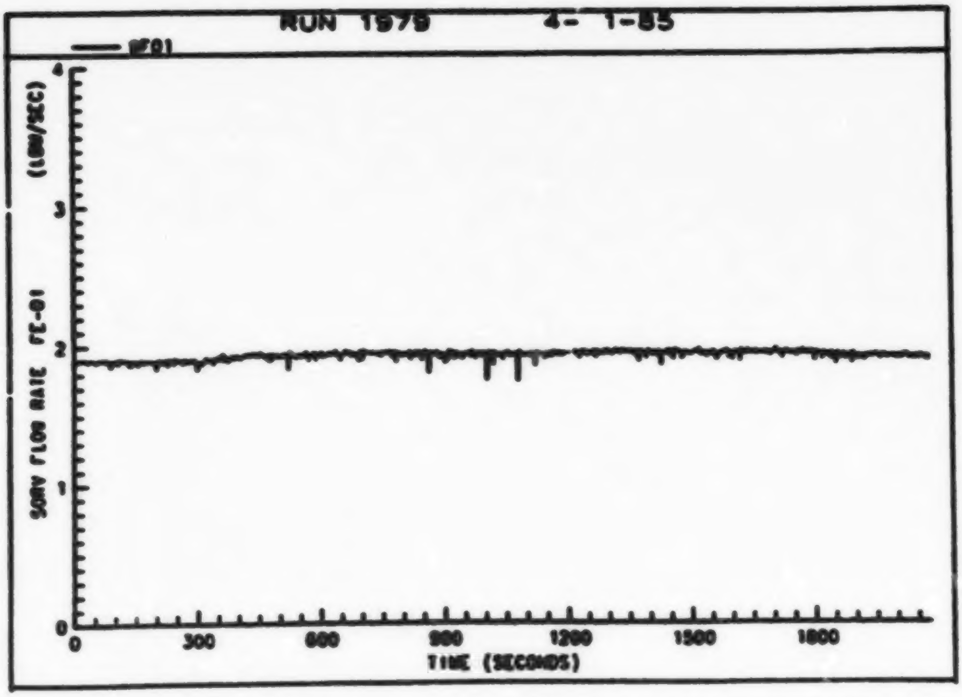

Figure 5-176. SORV Flow Rate (WF-01): Test No. 8 (T-1979)

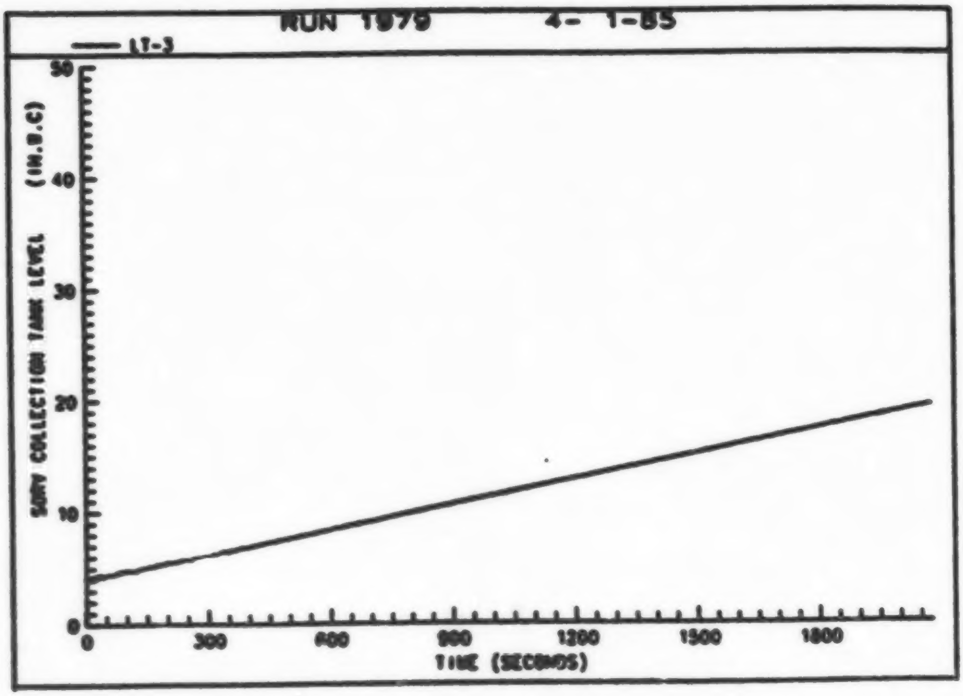

Figure 5-177. SORVTank Level (LT-3): Test No. 8 (T-1979)

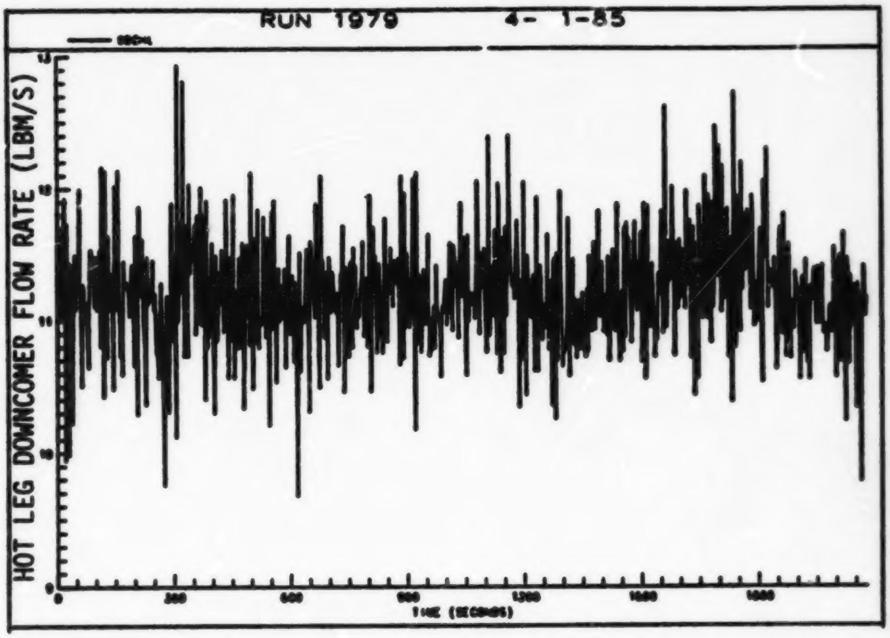

Figure 5-178. Hot Leg Downcomer Flow Rate (WDCHL): Test No. 8 (T-1979)

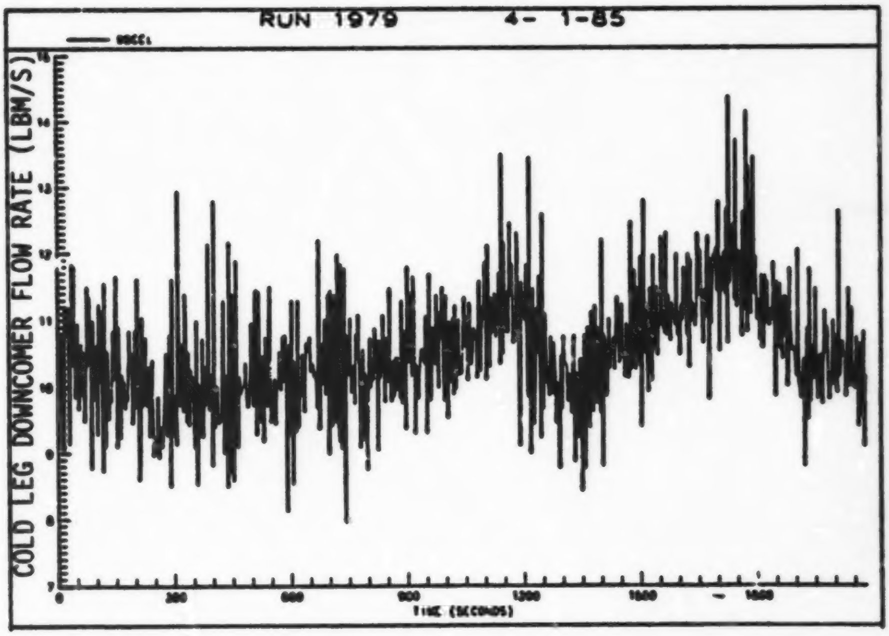

Figure 5-179. Cold Leg Downcomer Flow Rate (WDCCL): Test No. 8 (T-1979)

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281

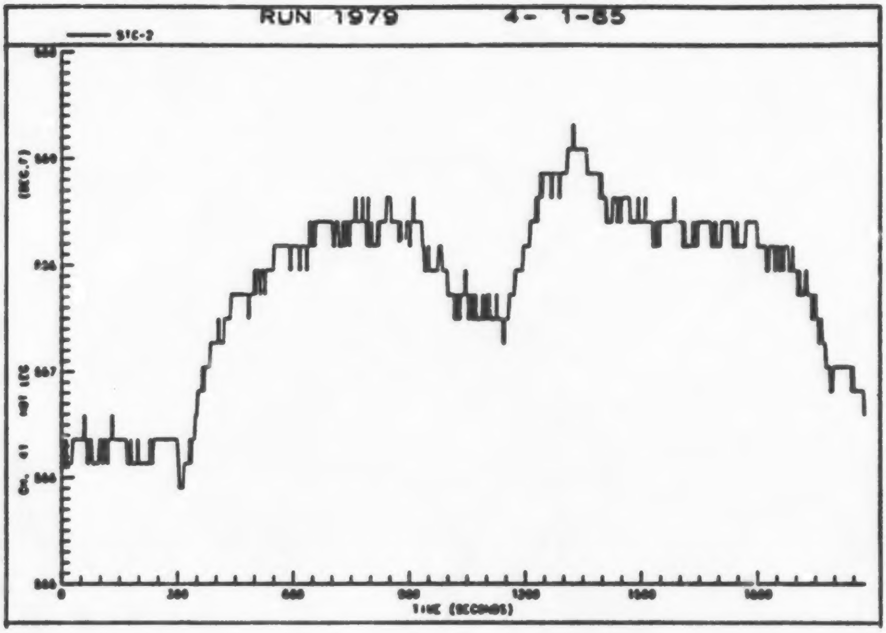

Figure 5-180. Secondary Fluid Temperature (STC-2): Test No. 8 (T-1979)

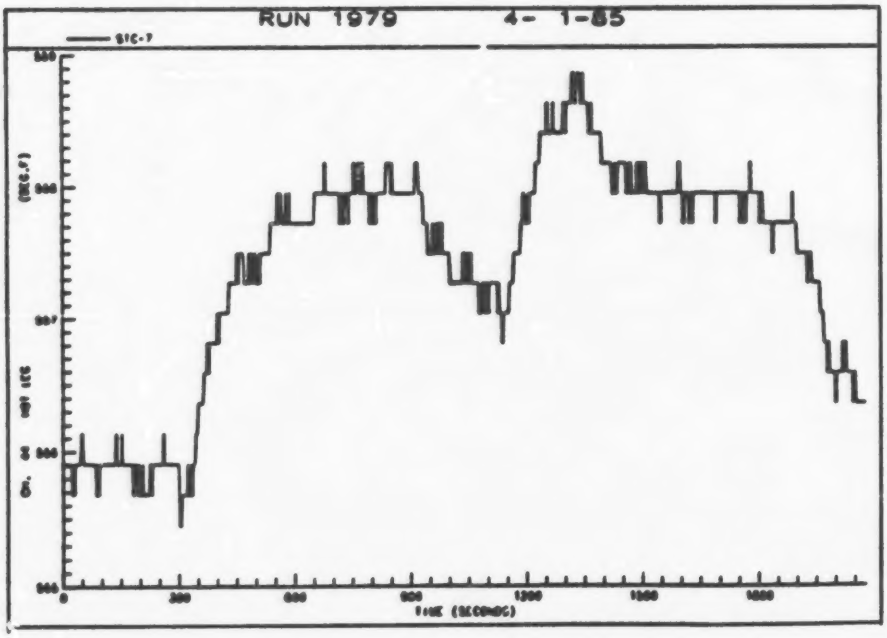

Figure 5-181. Secondary Fluid Temperature (STC-7): Test No. 8 (T-1979)

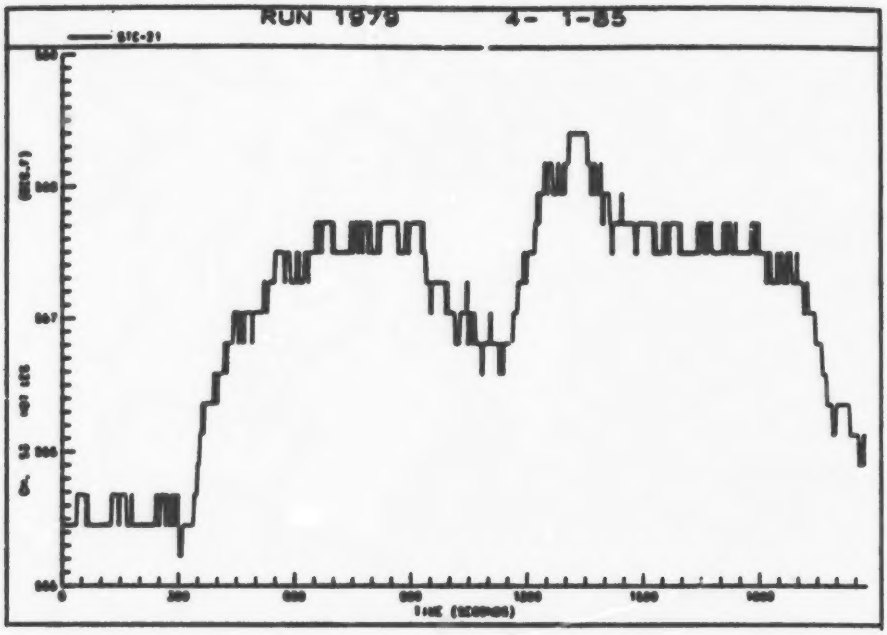

Figure 5-182. Secondary Fluid Temperature (STC-21): Test No. 8 (T-1979)

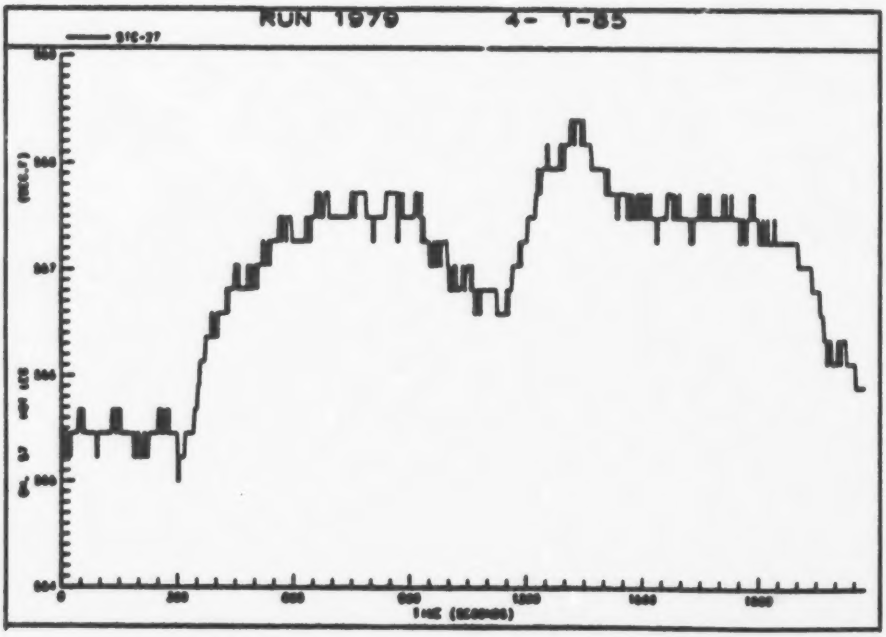

Figure 5-183. Secondary Fluid Temperature (STC-27): Test No. 8 (T-1979)

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283

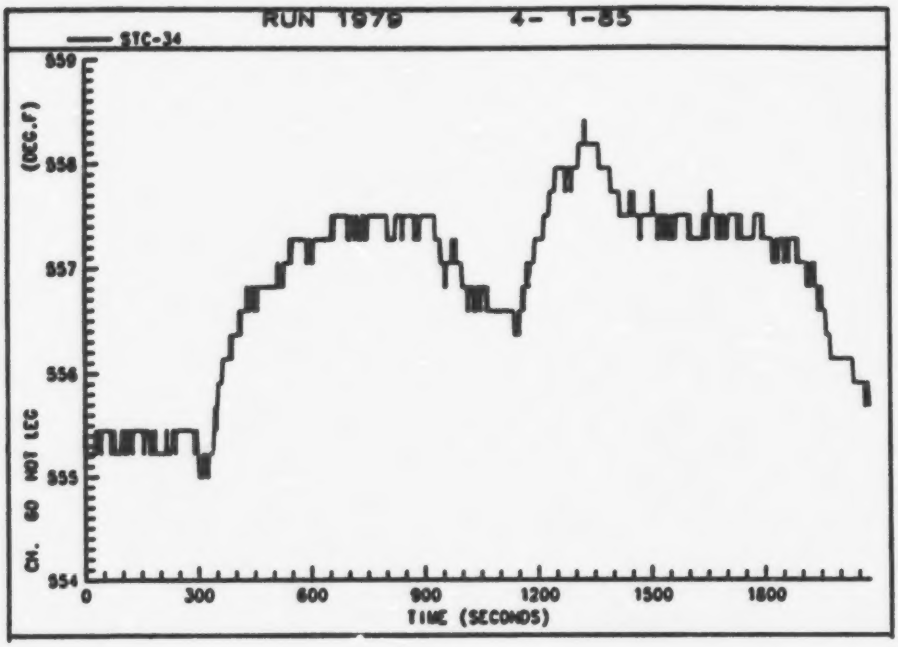

Figure 5-184. Secondary Fluid Temperature (STC-34): Test No. 8 (T-1979)

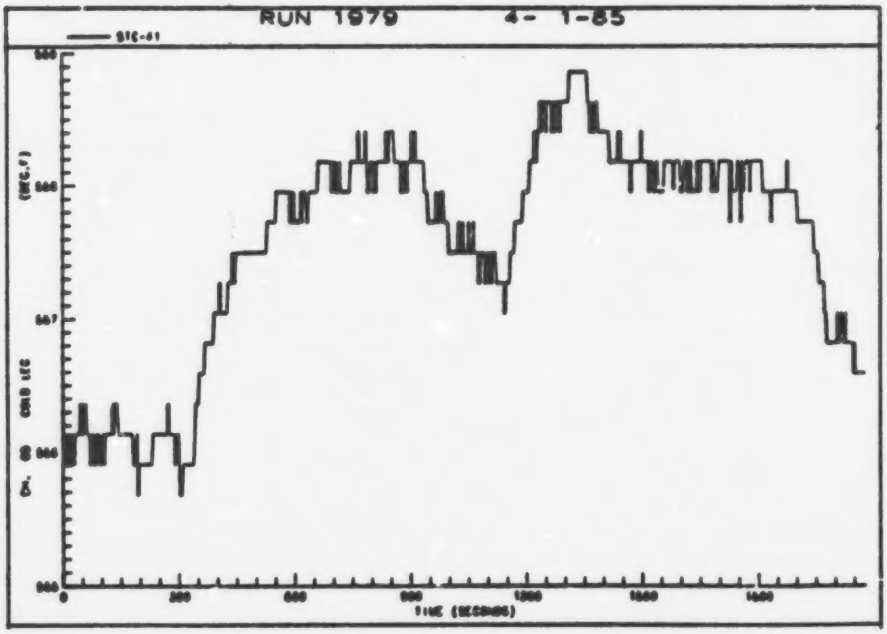

Figure 5-185. Secondary Fluid Temperature (STC-41): Test No. 8 (T-1979)

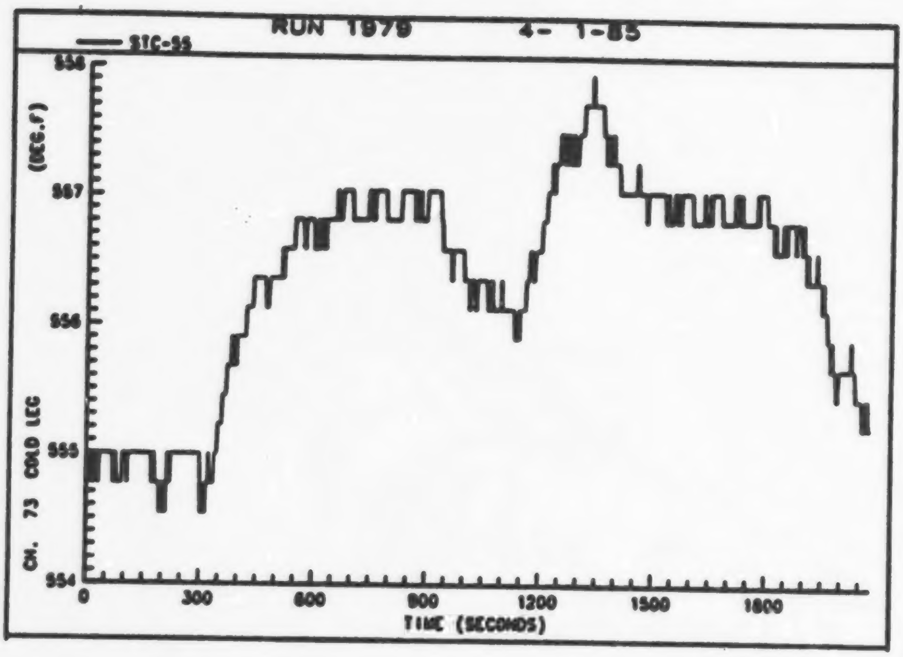

Figure 5-186. Secondary Fluid Temperature (STC-55): Test No. 8 (T-1979)

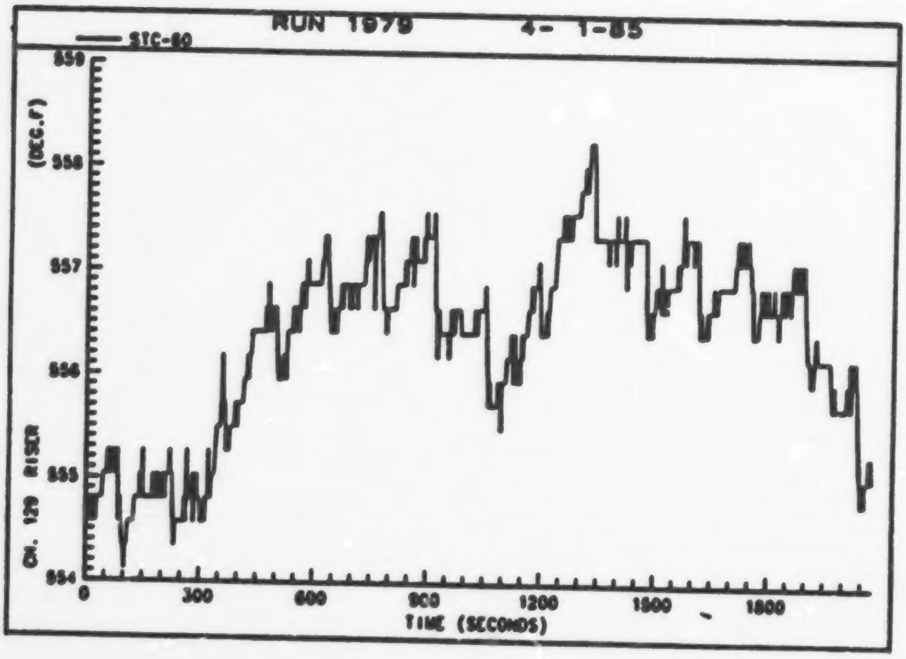

Figure 5-187. Secondary Fluid Temperature (STC-60) Test No. 8 (T-1979)

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285

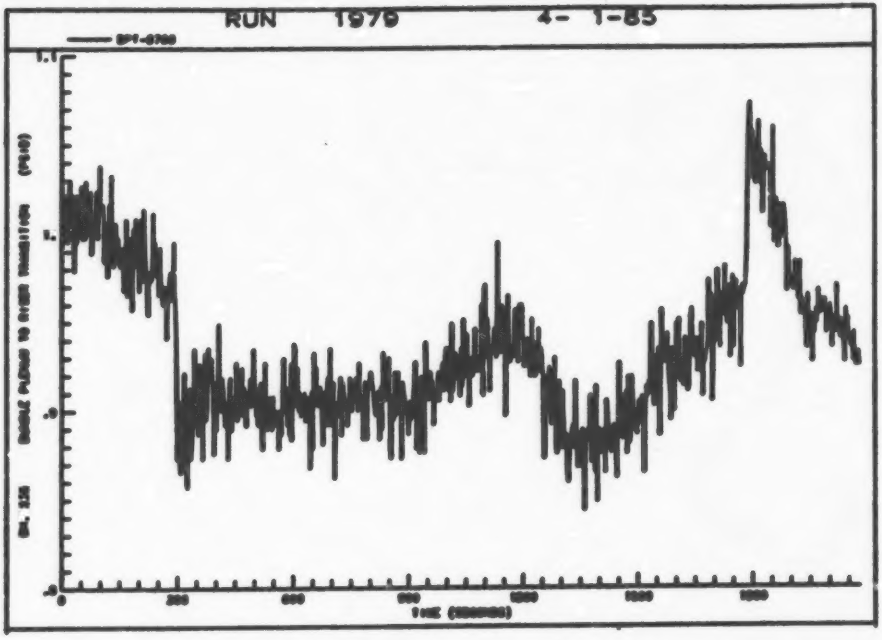

Figure 5-188. Differential Pressure DP-0760: Test No. 8 (T-1979)

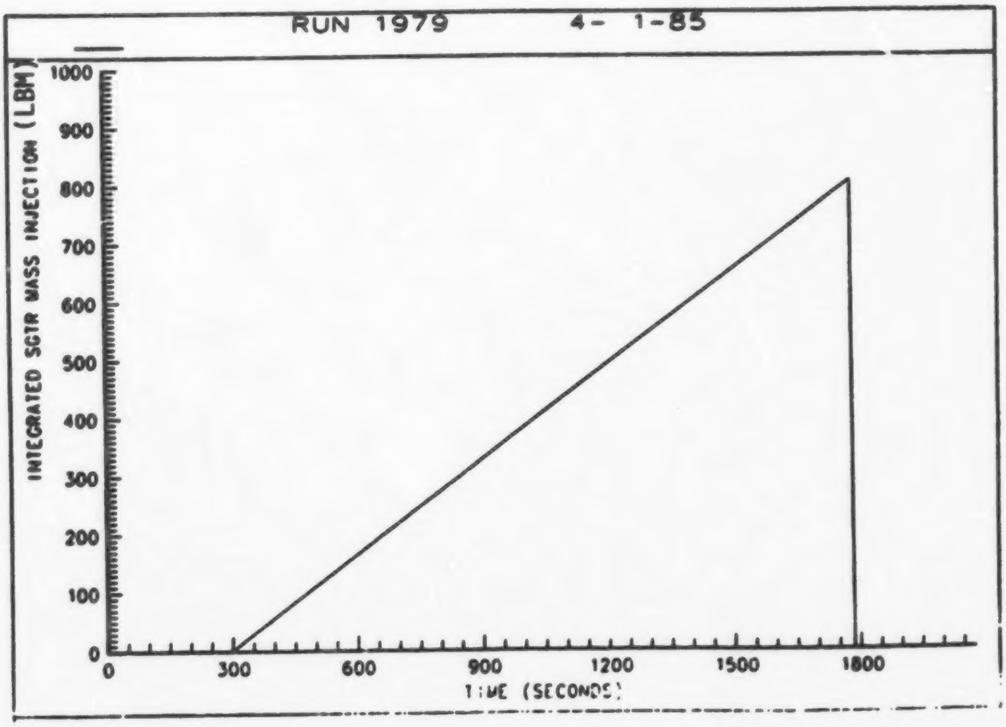

Figure 5-189. Integrated SGTR Flow: Test No. 9 (T-1979)

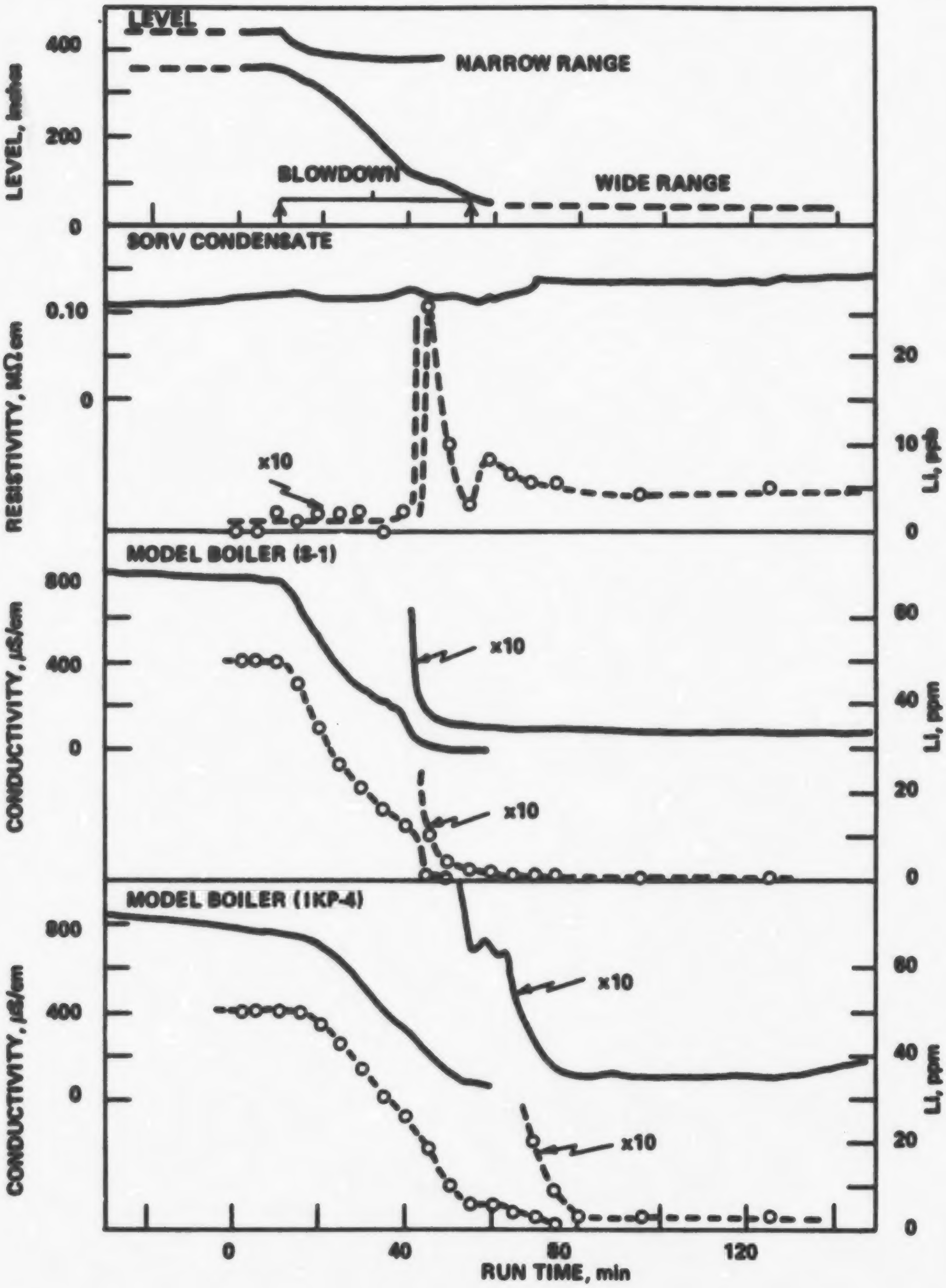

Figure 5-190. Variation in Tracer Concentrations: Blowdown Phase, Test No. 8 (T-1975)

— LEVEL, RESISTIVITY OR CONDUCTIVITY

—○— LITHIUM CONCENTRATION

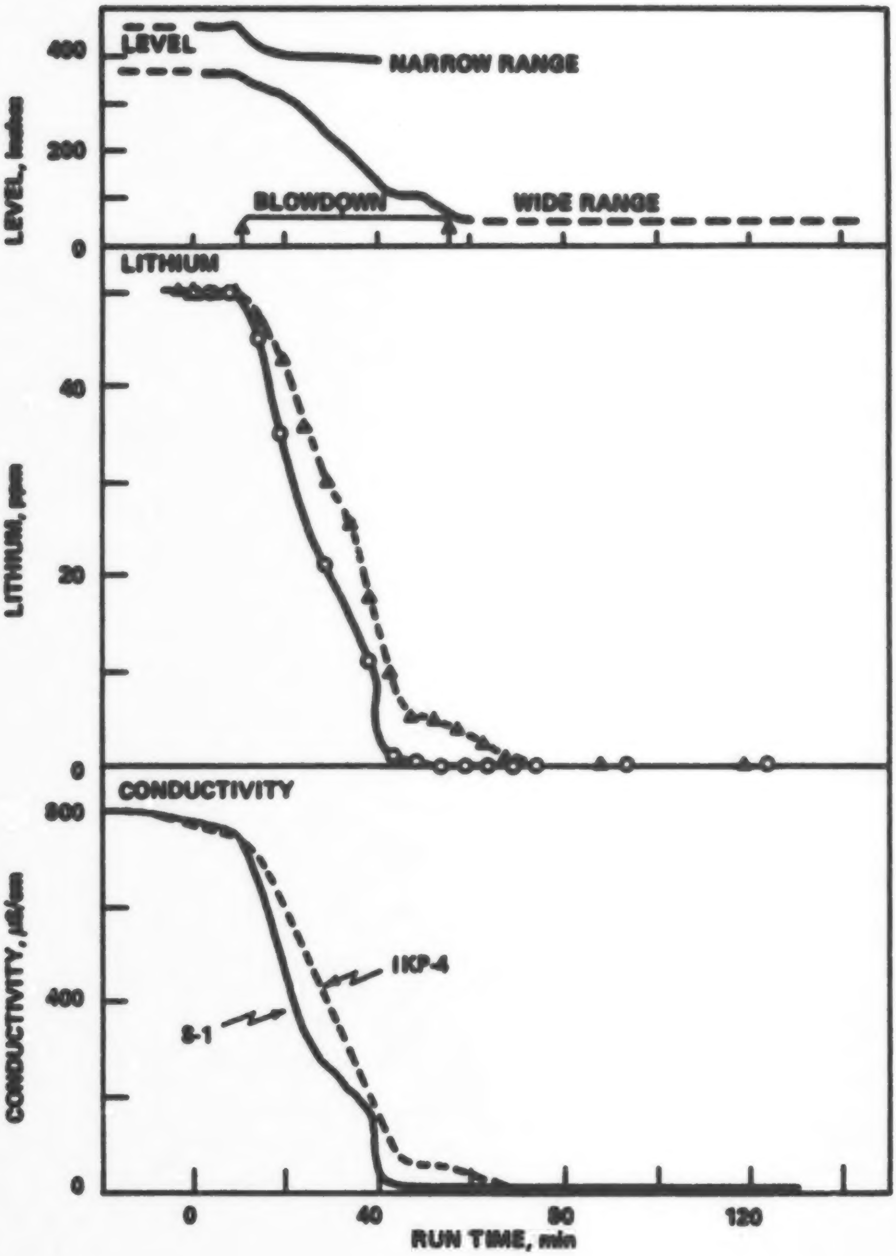

Figure 5-191. Comparison Between S-1 (○) and IKP-4 (▲) Results After Correcting for Sample Line Delays: Blowdown Phase, Test No. 8 (T-1975)

288

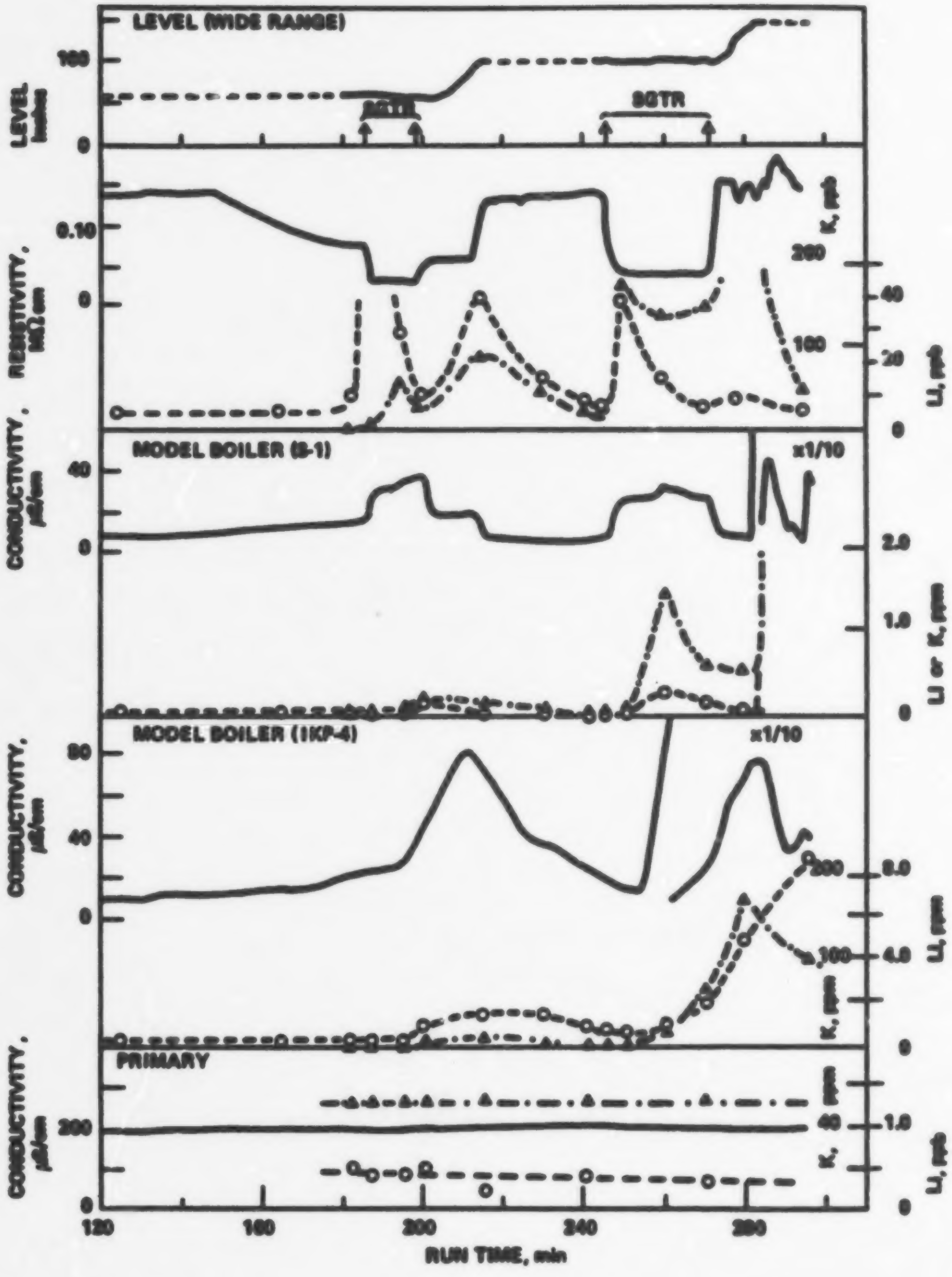

Figure 5-192. Variation in Tracer Concentrations: SGTRs at 62 and 104 in. Test No. 8 (T-1976 and T-1977)

—·▲—· POTASSIUM CONCENTRATION

——— LEVEL, RESISTIVITY OR CONDUCTIVITY

——○—— LITHIUM CONCENTRATION

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289

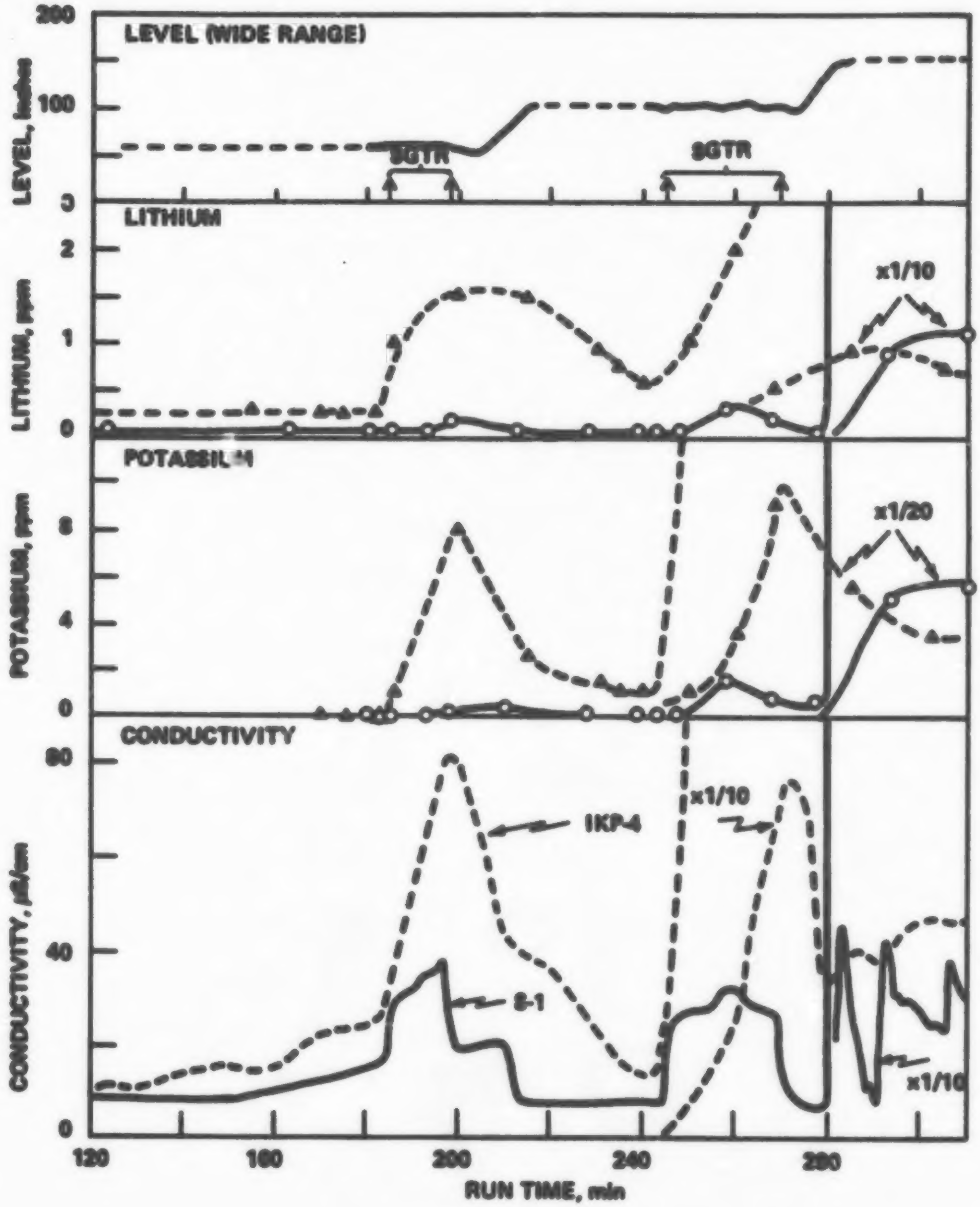

Figure 5-193. Comparison Between S-1 (○) and IKP-4 (▲) Results After Correcting for Sample Line Delays: SGTRs at 62 and 104 in., Test No. 8 (T-1976 and T-1977)

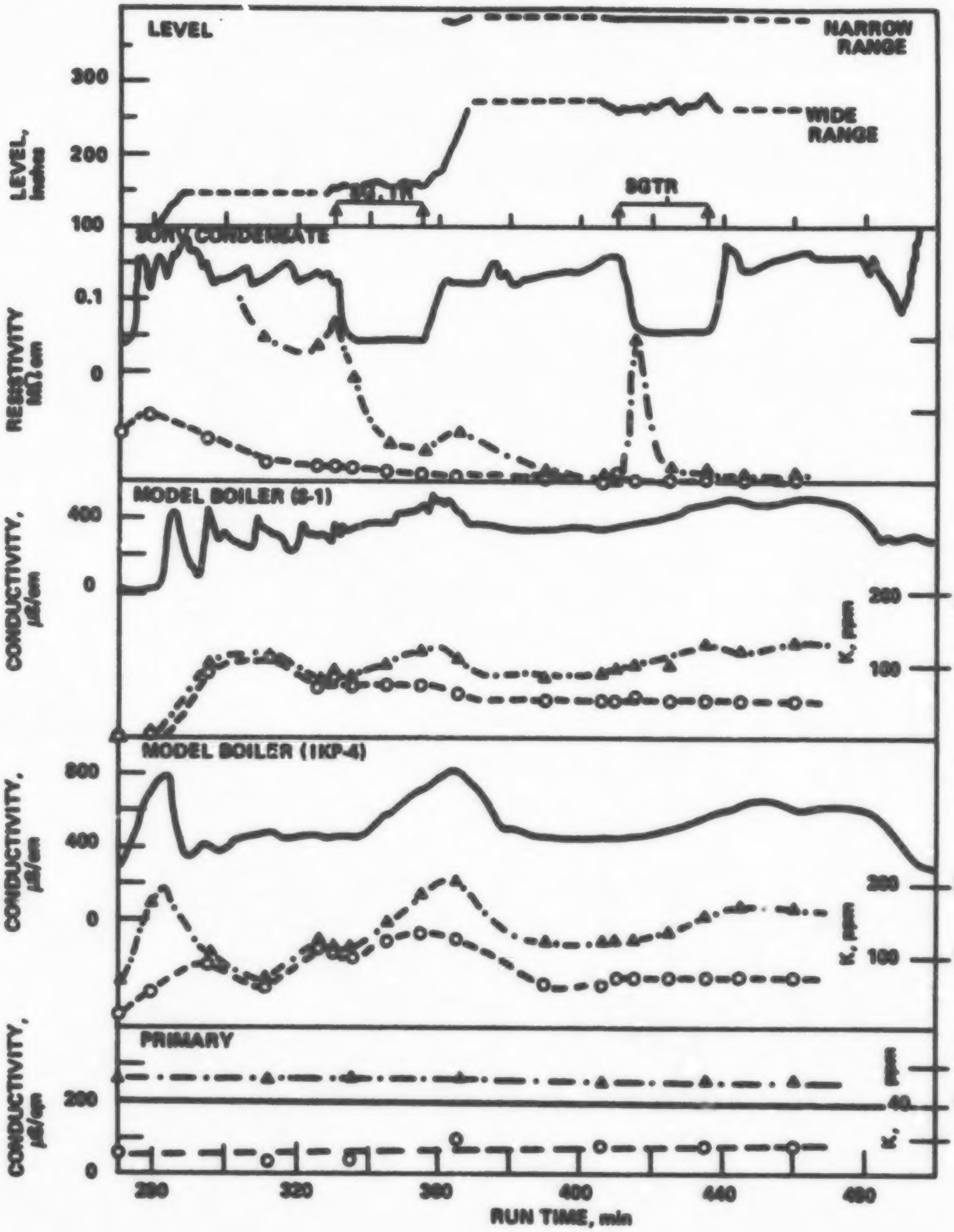

Figure 5-194. Variation in Tracer Concentrations: SGTRs at 160 and 280 in., Test No. 8 (T-1978 and T-1979)

—·▲—· POTASSIUM CONCENTRATION

——— LEVEL, RESISTIVITY OR CONDUCTIVITY

—○— LITHIUM CONCENTRATION

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291

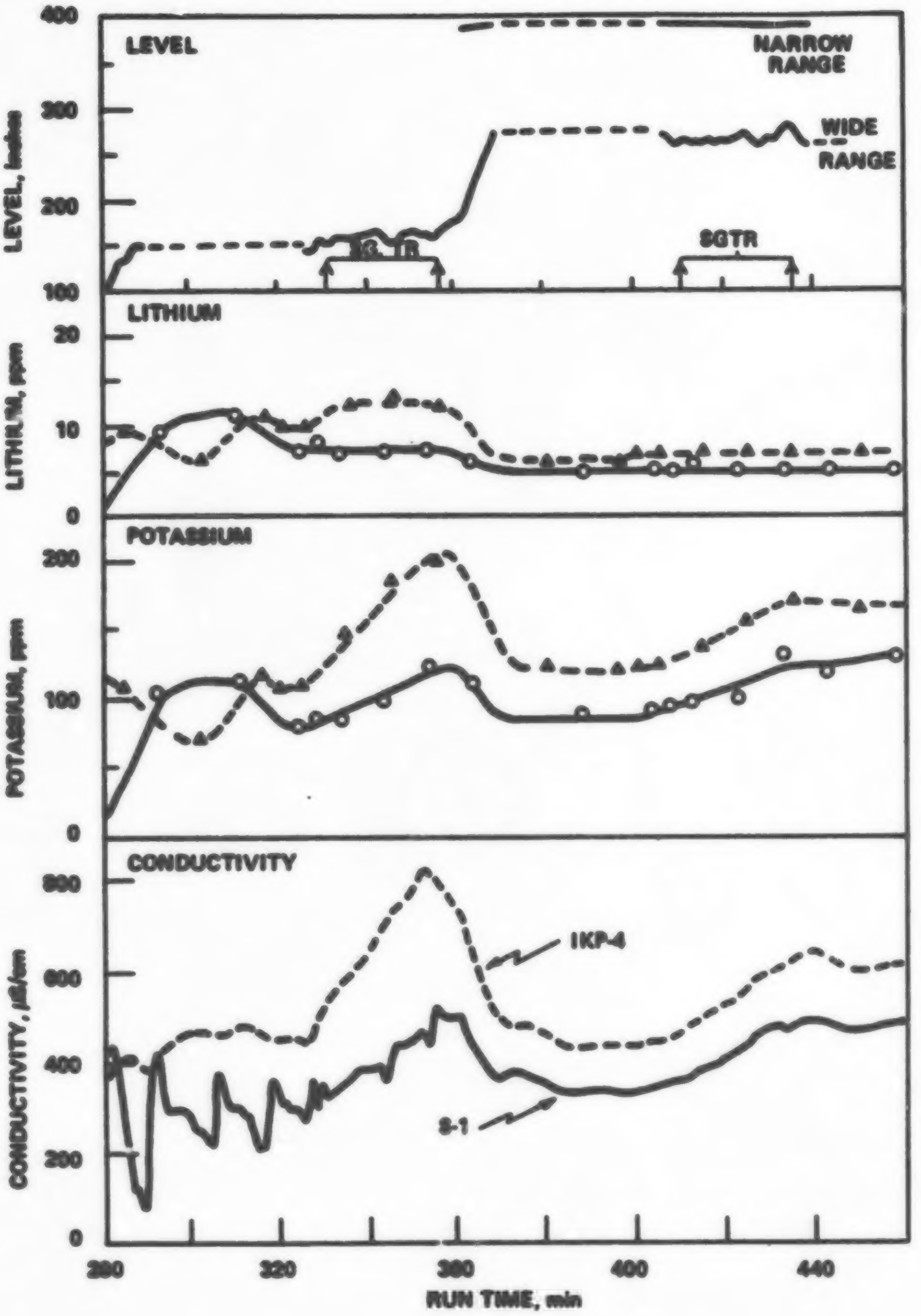

Figure 5-195. Comparison Between S-1 (○) and IKP-4 (▲) Results After Correcting for Sample Line Delays: SGTRs at 160 and 280 in., Test No. 8 (T-1978 and T-1979)

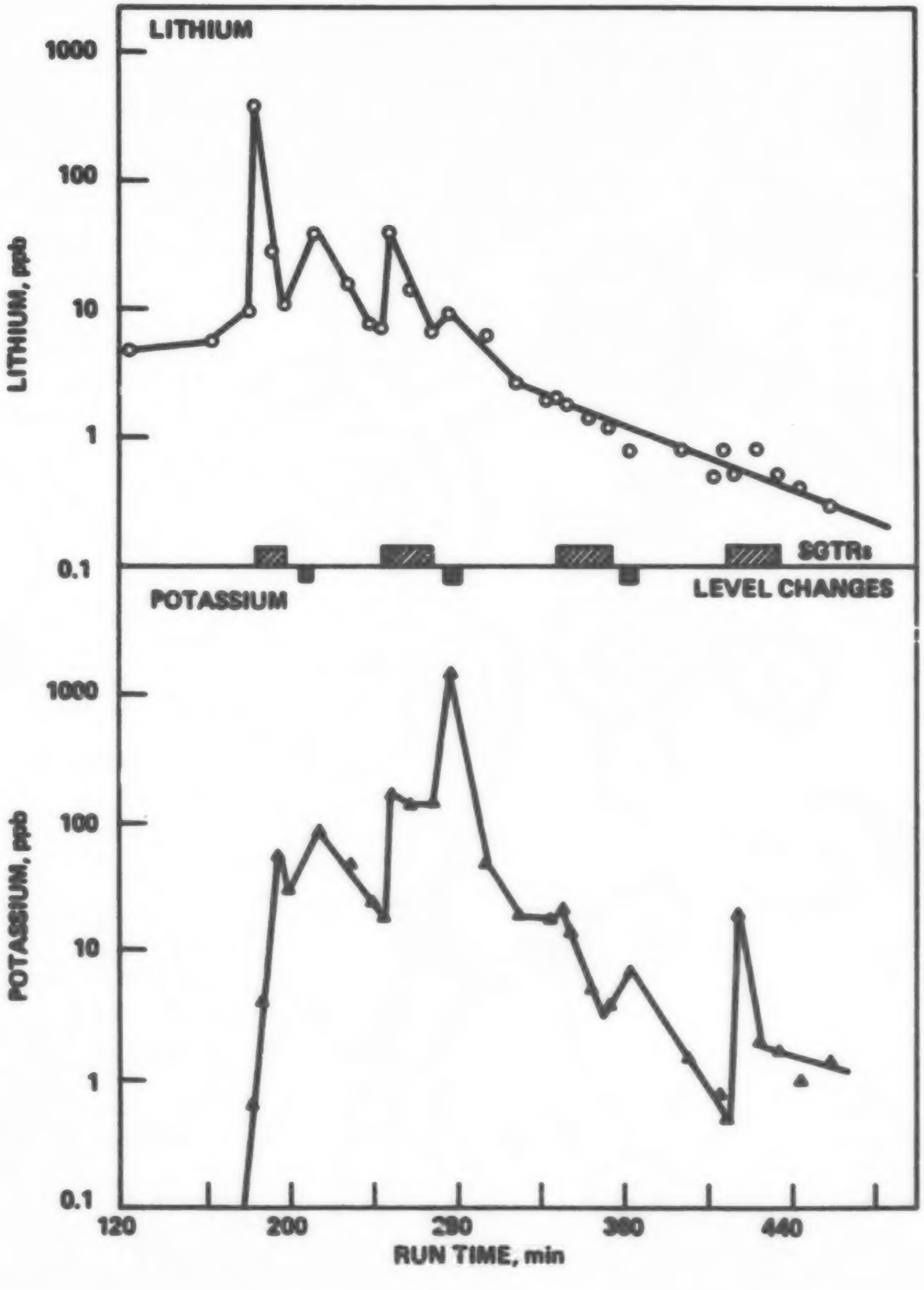

Figure 5-196. Variation in SORV Condensate Tracer Concentrations After Correcting for Sample Line Delays: Test No. 8 (T-1975 to T-1979)

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293

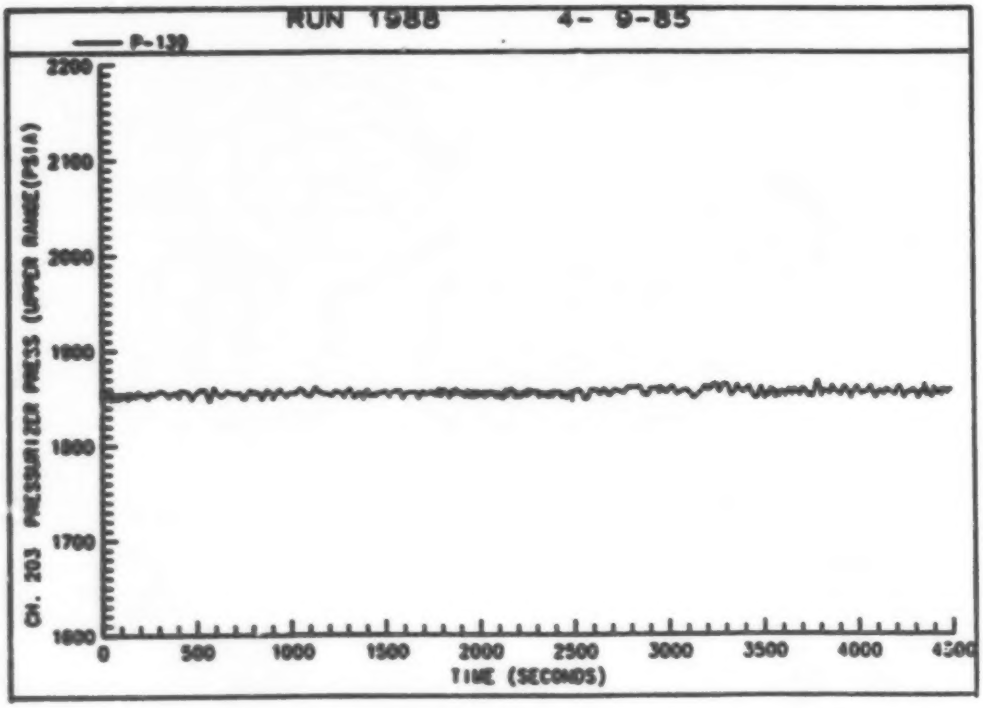

Figure 5-197. Primary System (Pressurizer) Pressure (P-139): Test No. 9 (T-1988)

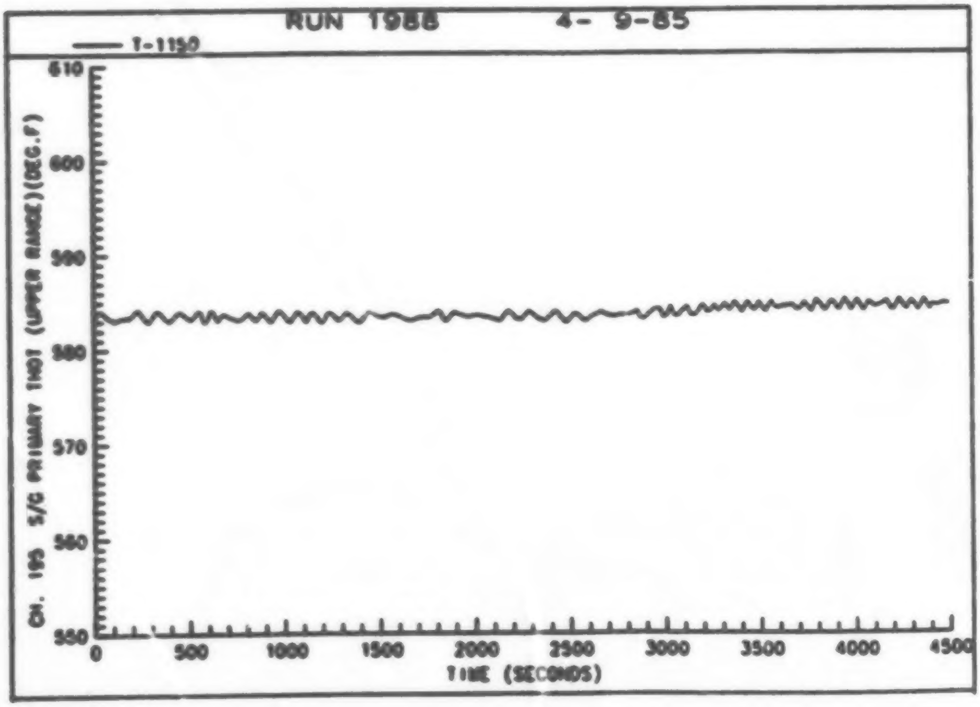

Figure 5-198. Primary Fluid T_{hot} (T-1150): Test No. 9 (T-1988)

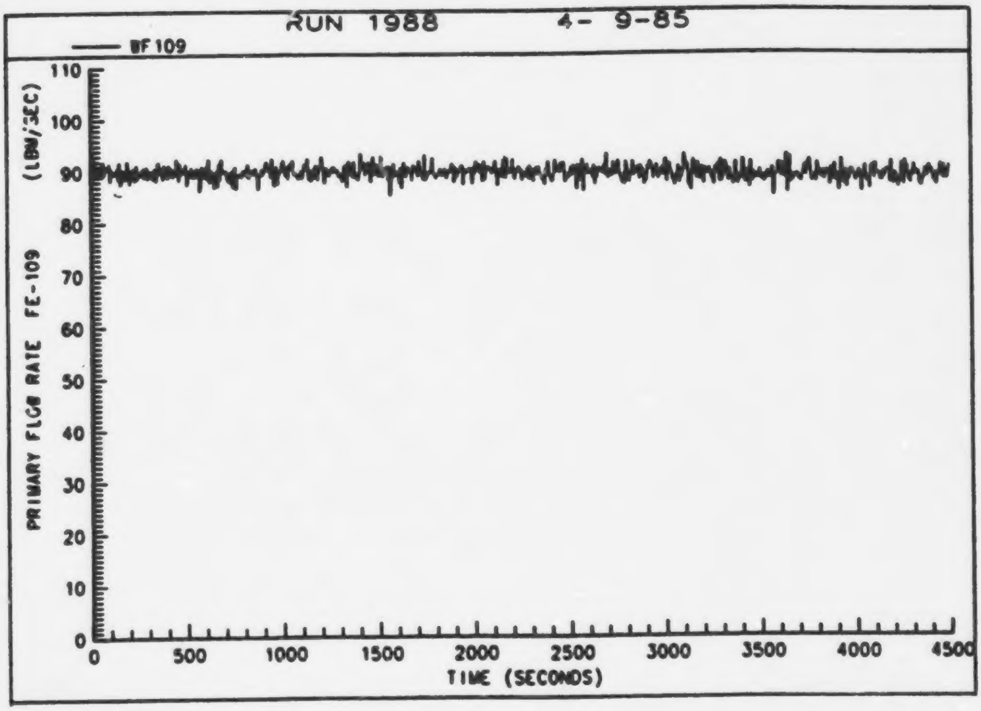

Figure 5-199. Primary Fluid Flow Rate (WF-109): Test No. 9 (T-1988)

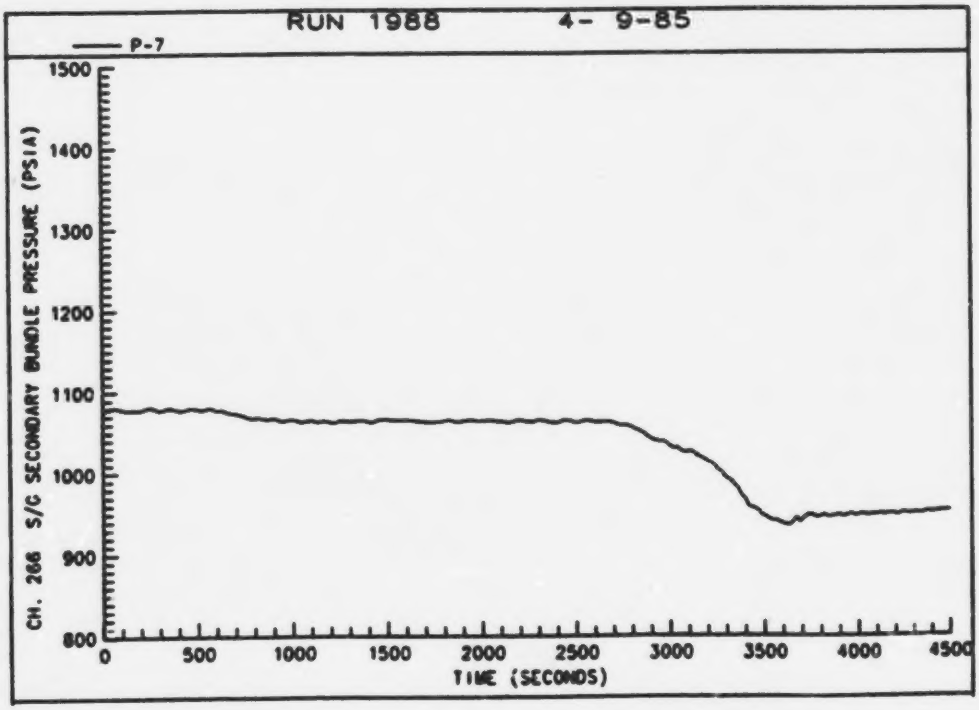

Figure 5-200. Secondary Side Pressure (P-7): Test No. 9 (T-1988)

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295

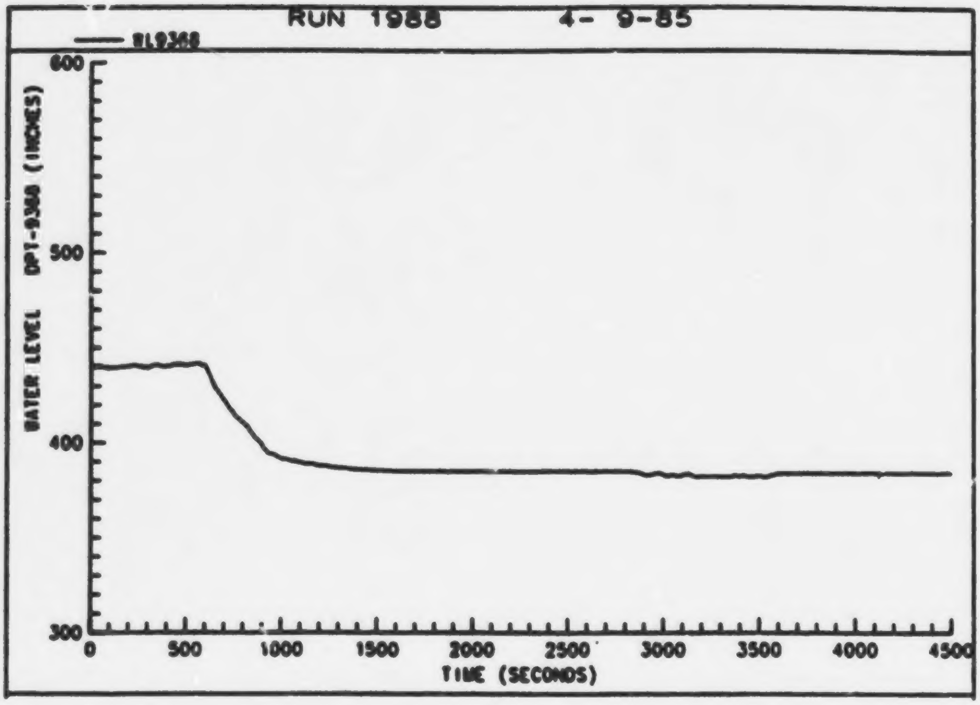

Figure 5-201. Downcomer Water Level - Narrow Range (WL-9368): Test No. 9 (T-1988)

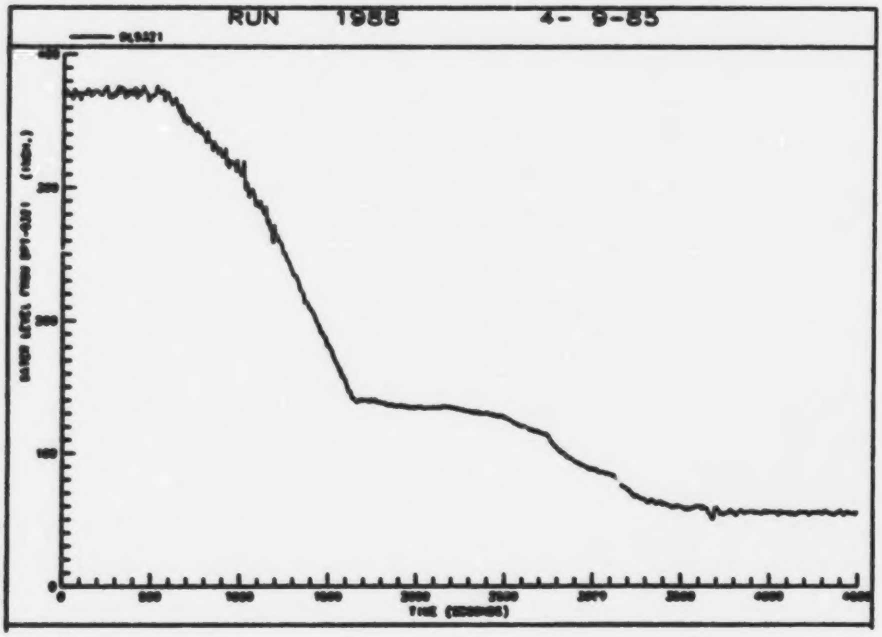

Figure 5-202. Downcomer Water Level - Wide Range (WL-9321): Test No. 9 (T-1988)

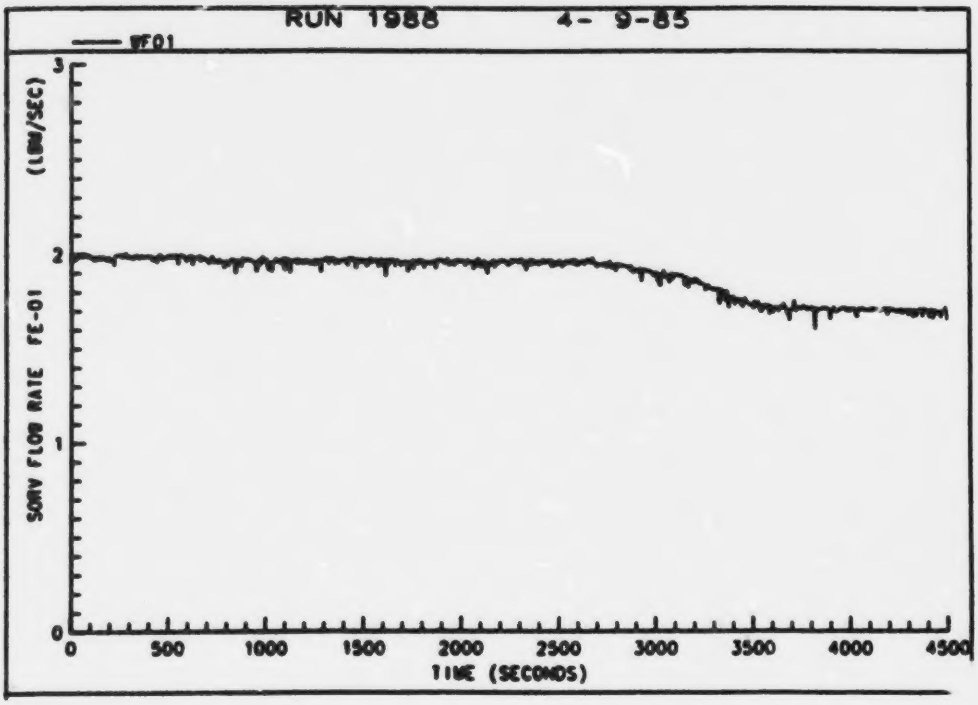

Figure 5-203. SORV Flow Rate (WF-01): Test No. 9 (T-1988)

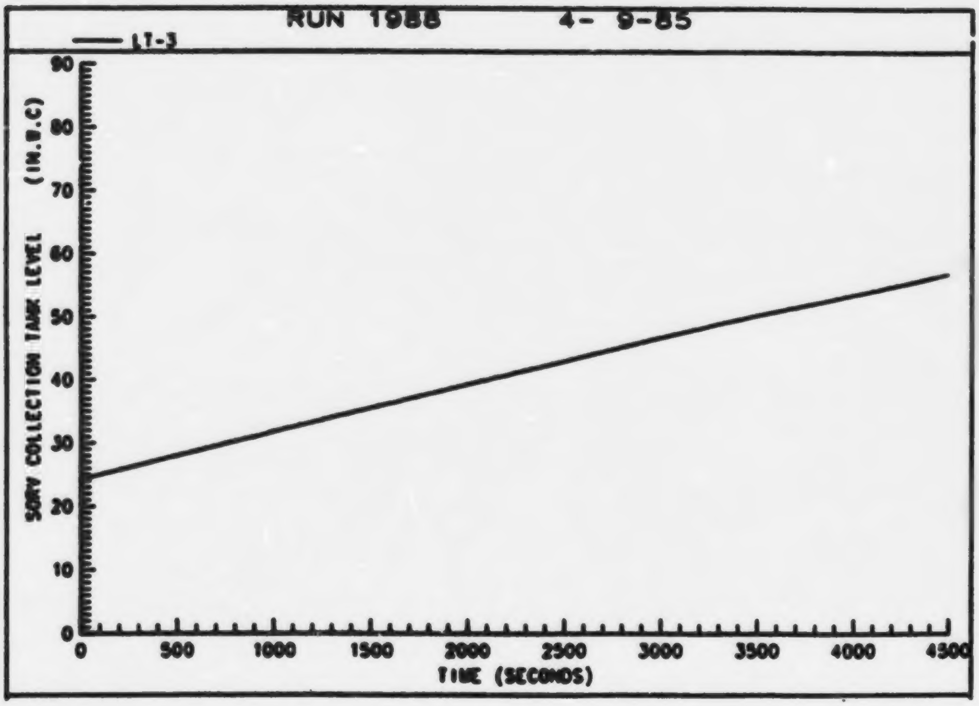

Figure 5-204. SORV Tank Level (LT-3): Test No. 9 (T-1988)

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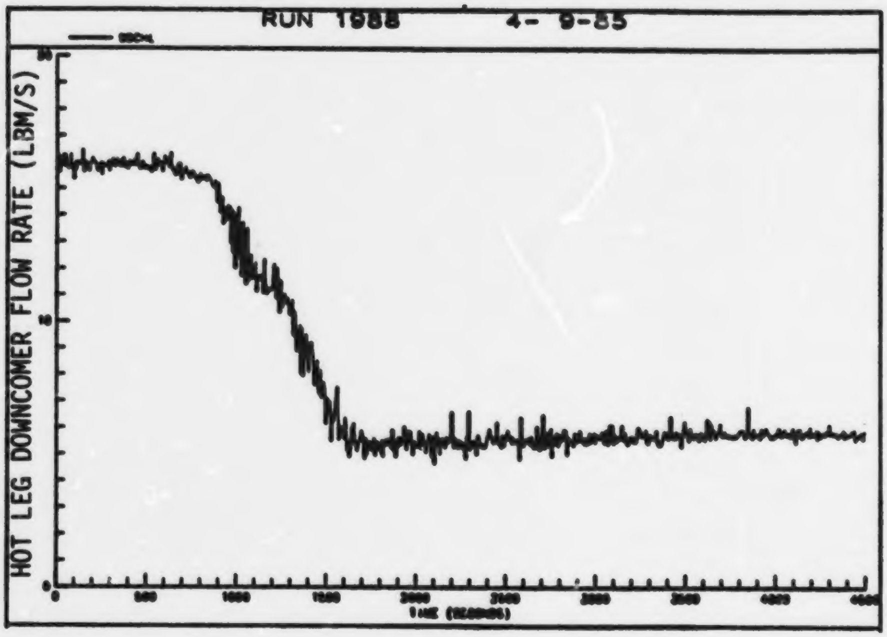

Figure 5-205. Hot Leg Downcomer Flow Rate (WDCHL): Test No. 9 (T-1988)

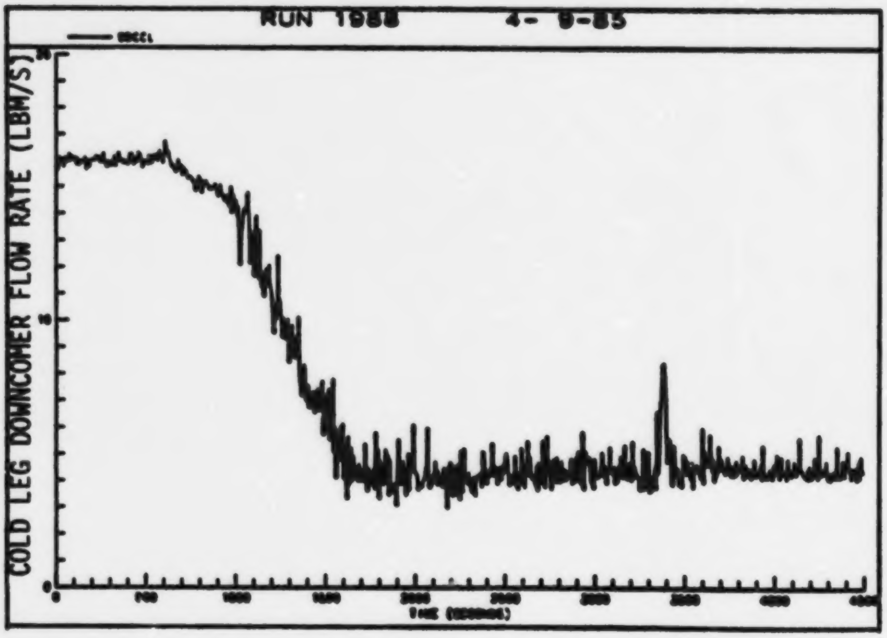

Figure 5-206. Cold Leg Downcomer Flow Rate (WDCCL): Test No. 9 (T-1988)

298

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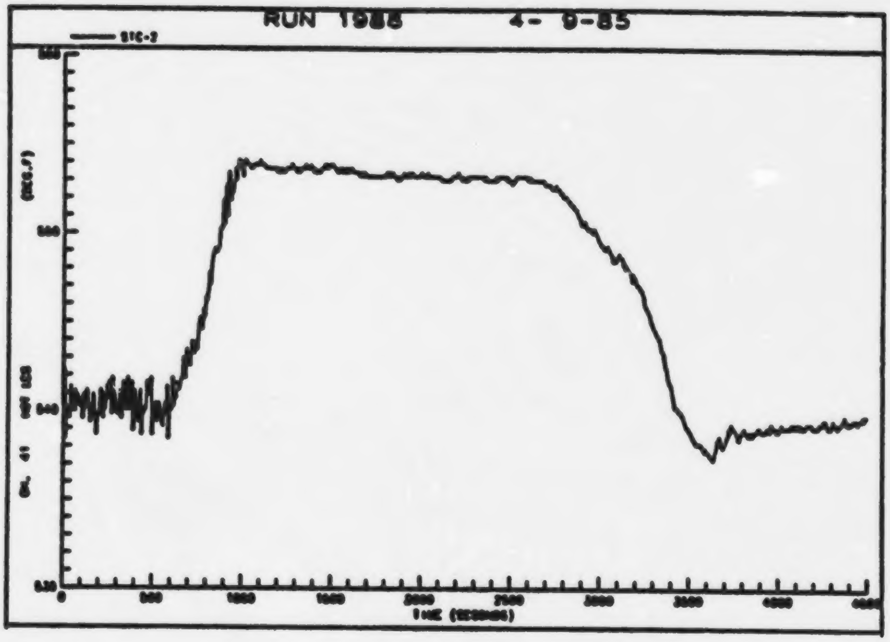

Figure 5-207. Secondary Fluid Temperature (STC-2): Test No. 9 (T-1988)

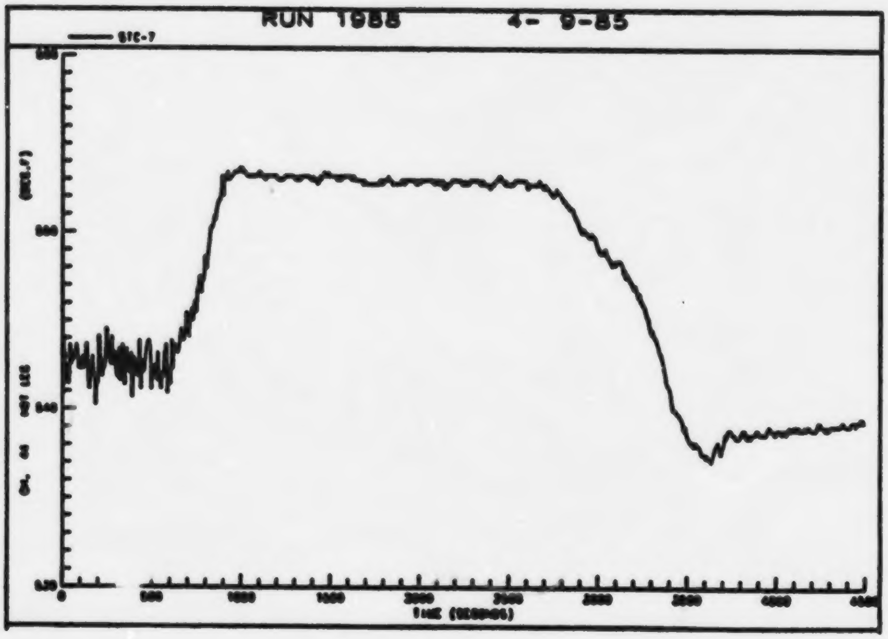

Figure 5-208. Secondary Fluid Temperature (STC-7): Test No. 9 (T-1988)

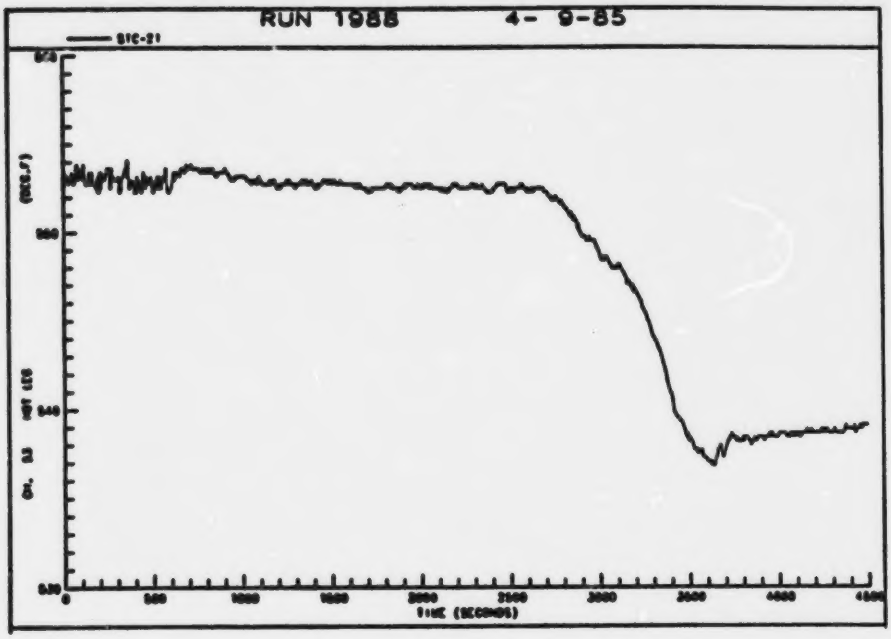

Figure 5-209. Secondary Fluid Temperature (STC-21): Test No. 9 (T-1988)

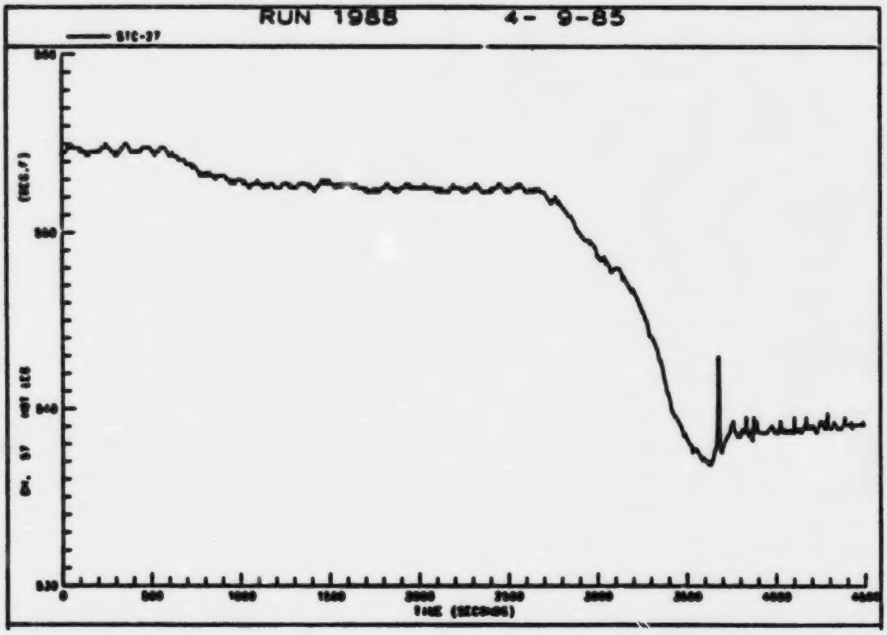

Figure 5-210. Secondary Fluid Temperature (STC-27): Test No. 9 (T-1988)

300

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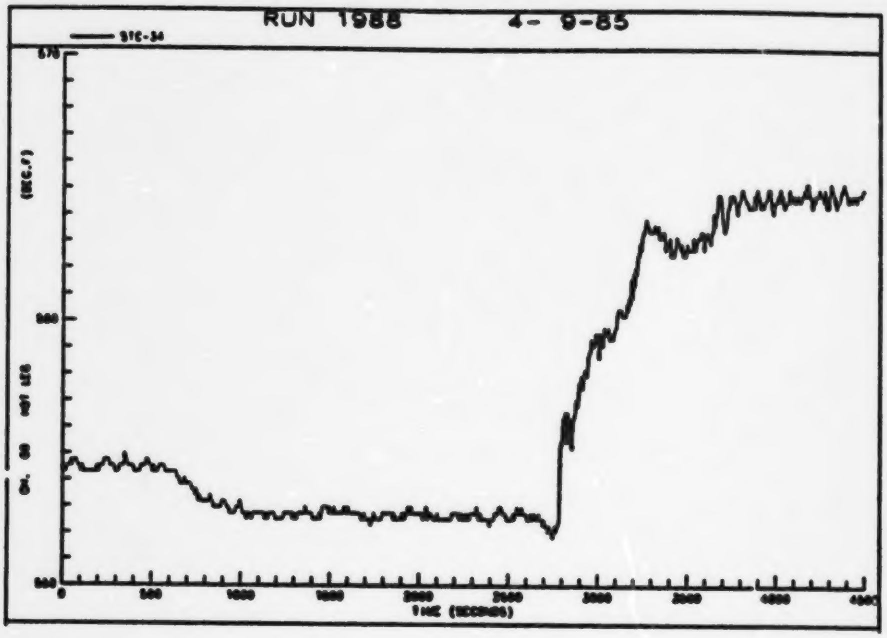

Figure 5-211. Secondary Fluid Temperature (STC-34): Test No. 9 (T-1988)

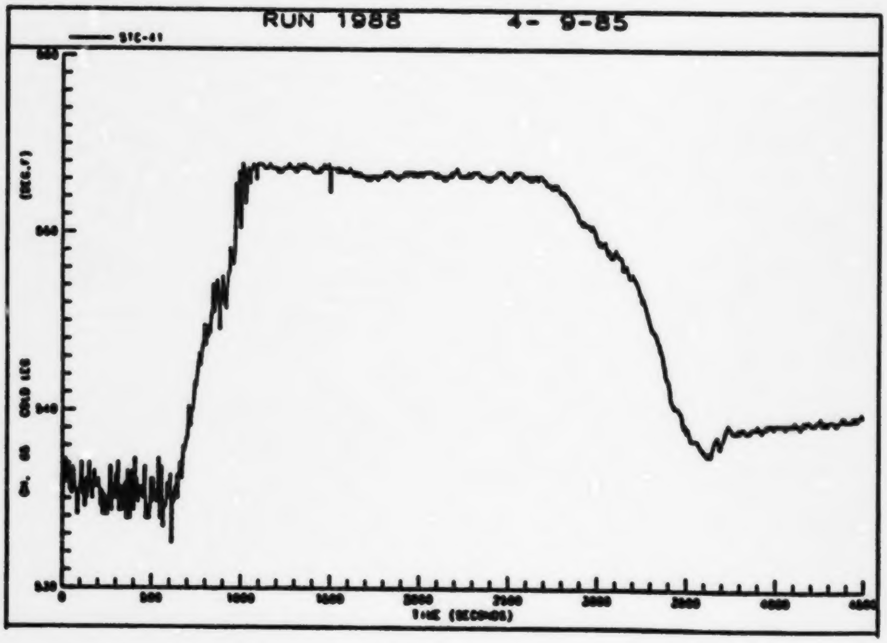

Figure 5-212. Secondary Fluid Temperature (STC-41): Test No. 9 (T-1988)

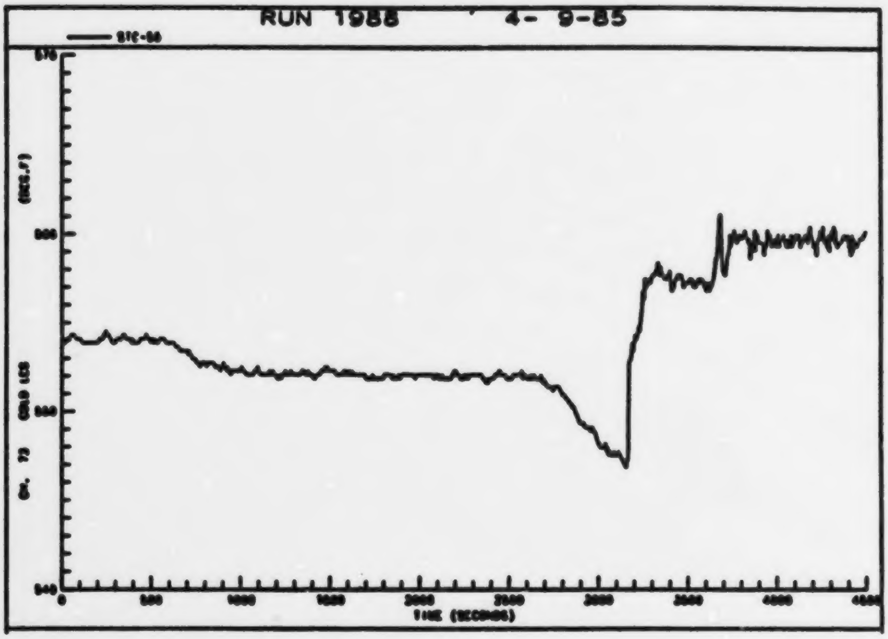

Figure 5-213. Secondary Fluid Temperature (STC-55): Test No. 8 (T-1988)

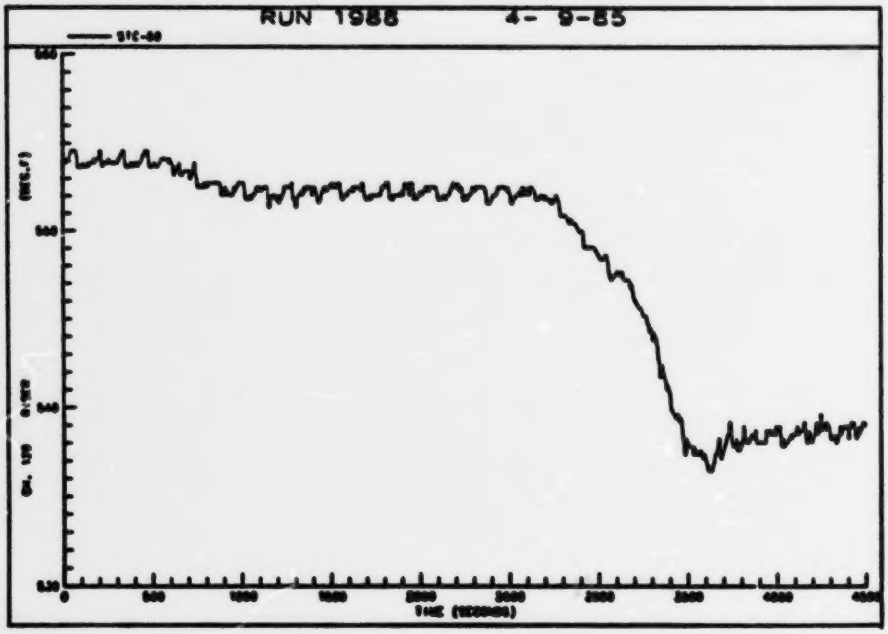

Figure 5-214. Secondary Fluid Temperature (STC-60): Test No. 9 (T-1988)

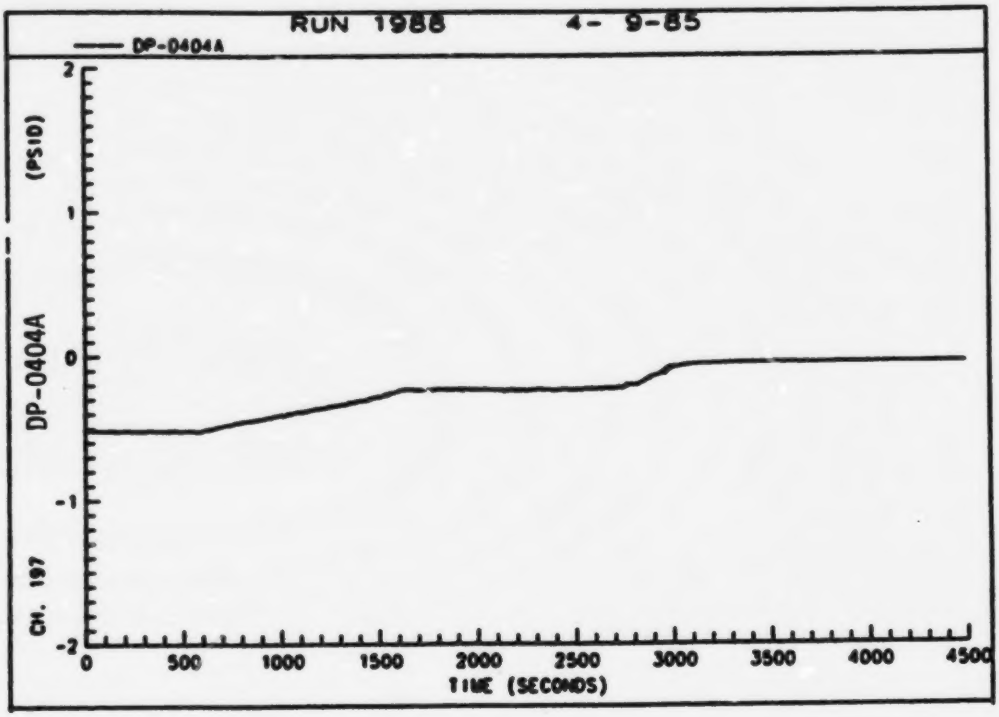

Figure 5-215. Differential Pressure, DP-0404A: Test No. 9 (T-1988)

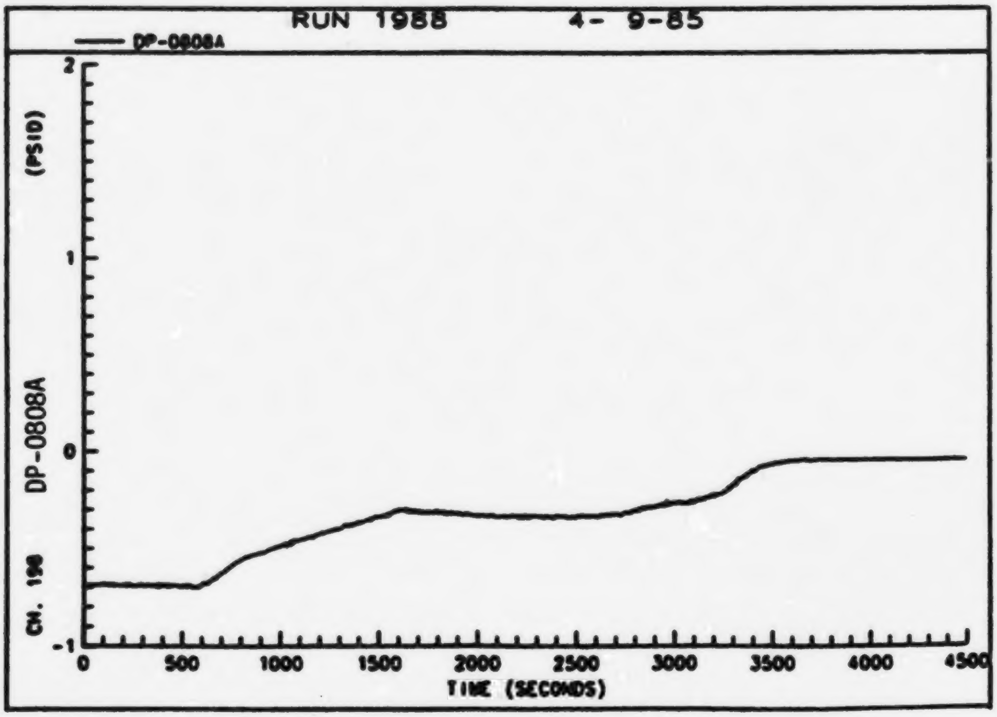

Figure 5-216. Differential Pressure, DP-0808A: Test No. 9 (T-1988)

303

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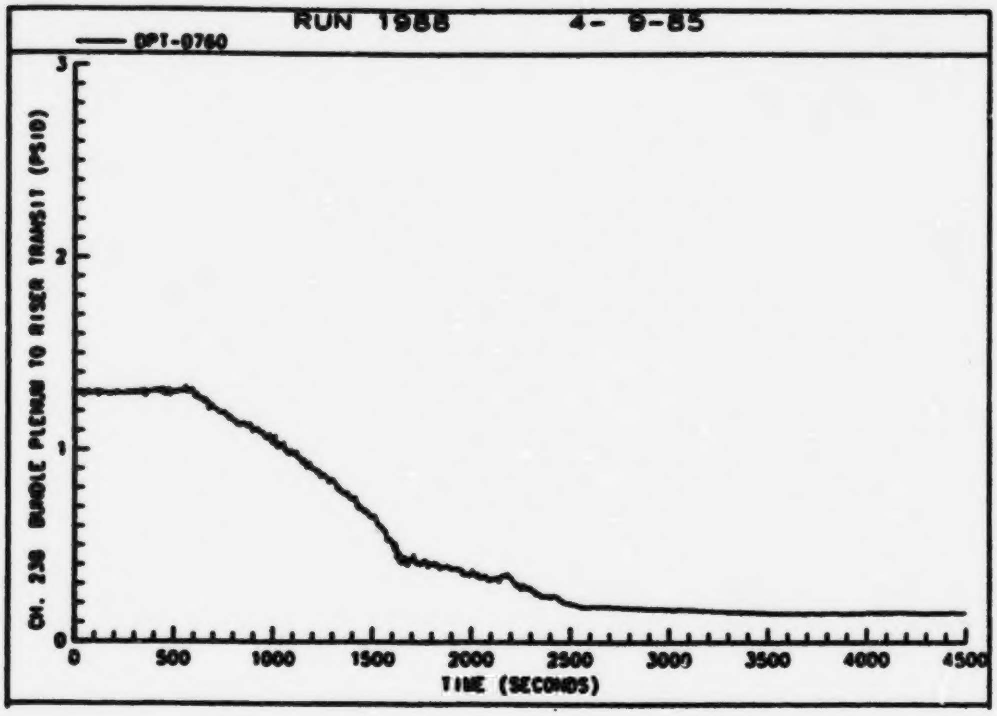

Figure 5-217. Differential Pressure DP-0760: Test No. 9 (T-1988)

304

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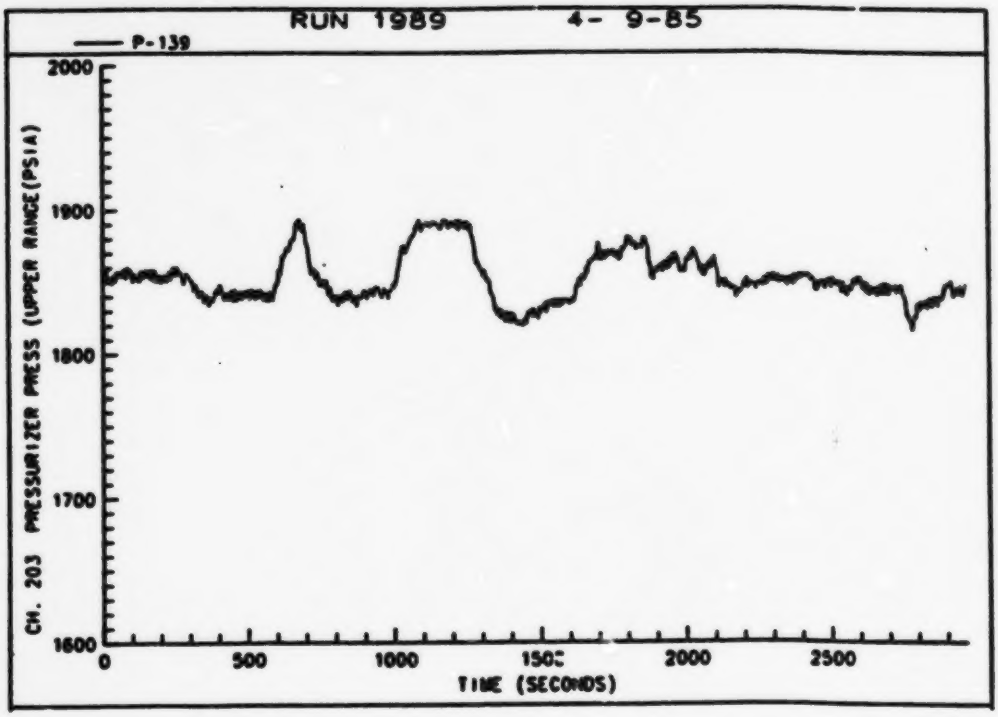

Figure 5-218. Primary System (Pressurizer) Pressure (P-139): Test No. 9 (T-1989)

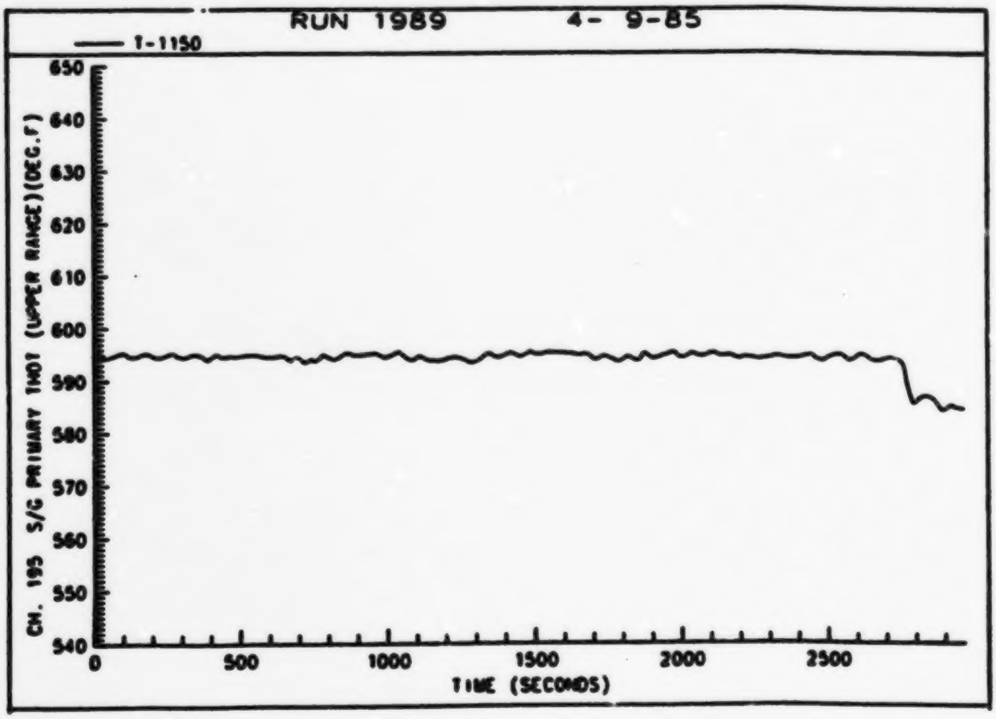

Figure 5-219. Primary Fluid T_{hot} (T-1150): Test No. 9 (T-1989)

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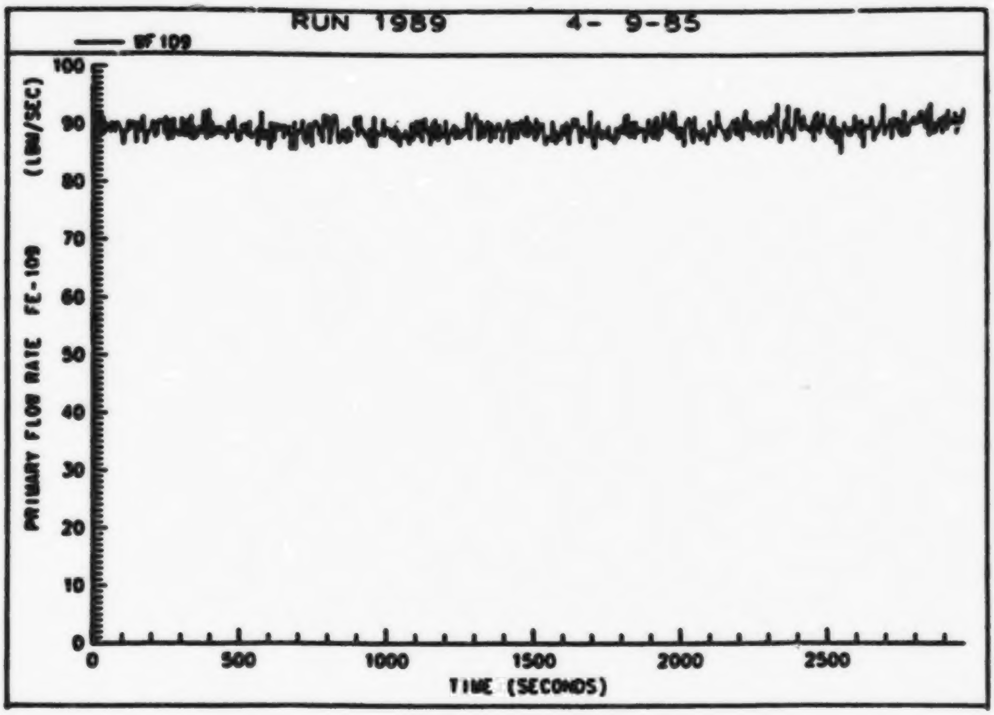

Figure 5-220. Primary Fluid Flow Rate (WF-109): Test No. 9 (T-1989)

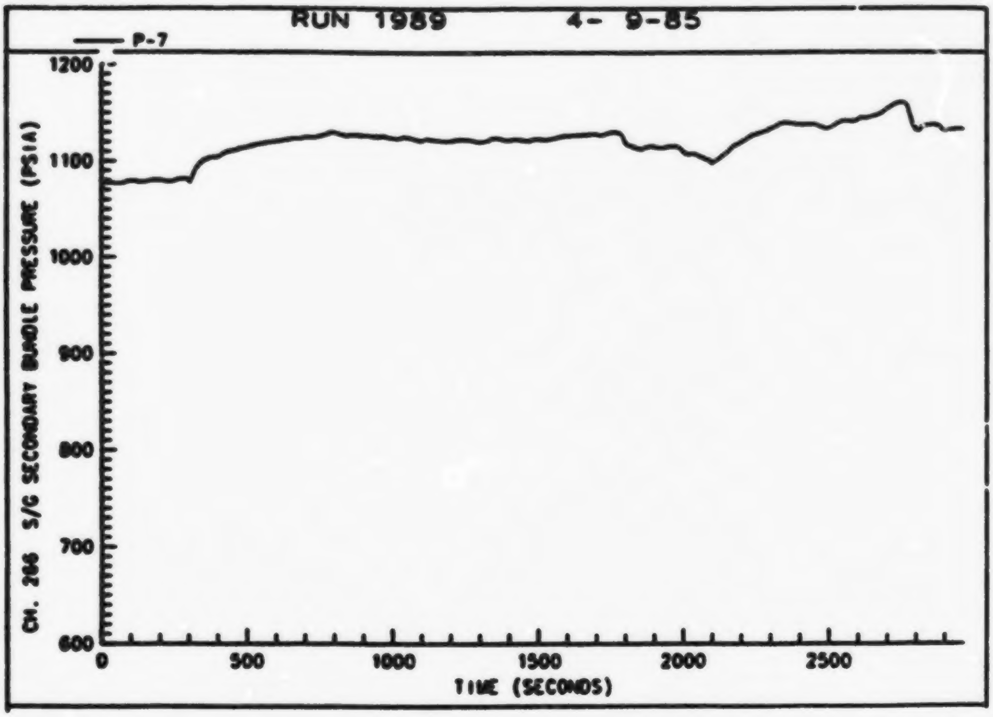

Figure 5-221. Secondary Side Pressure (P-7): Test No. 9 (T-1989)

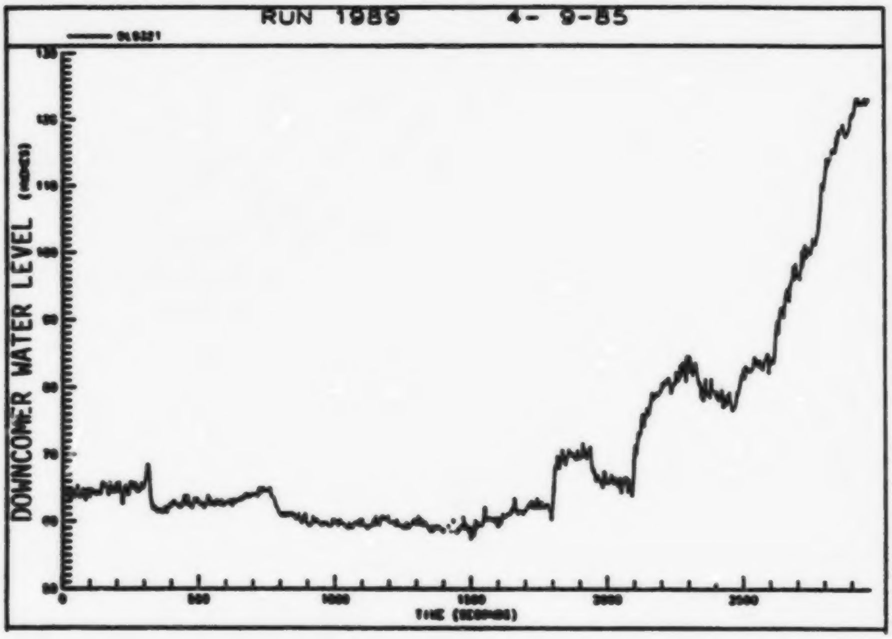

Figure 5-222. Downcomer Water Level - Wide Range (WL-9321): Test No. 9 (T-1989)

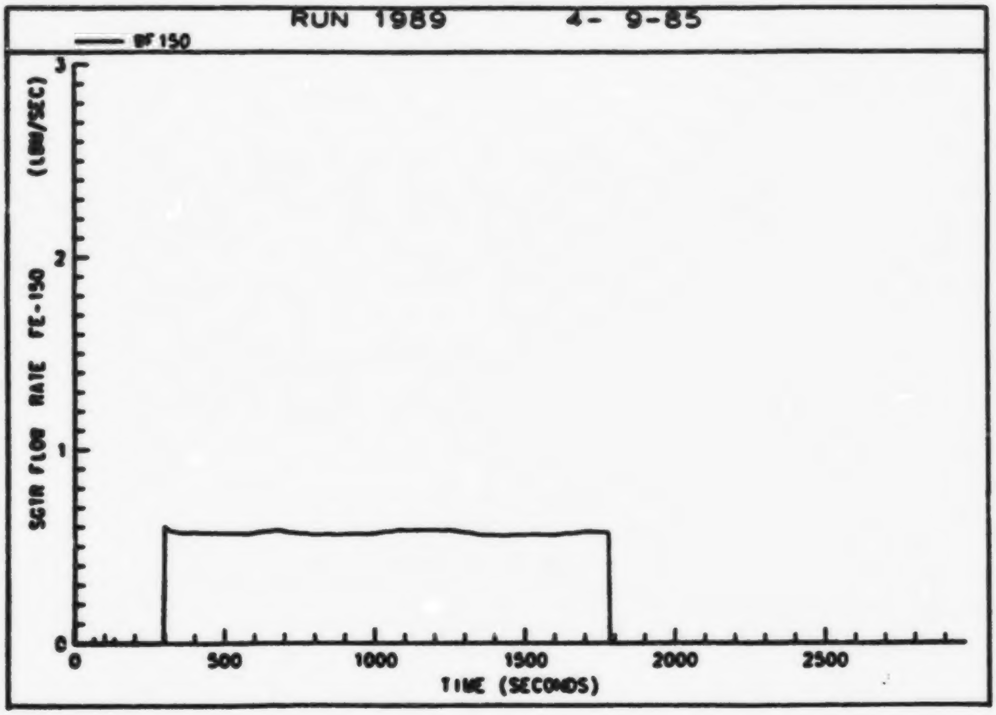

Figure 5-223. SGTR Flow Rate (WF-150): Test No. 9 (T-1989)

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307

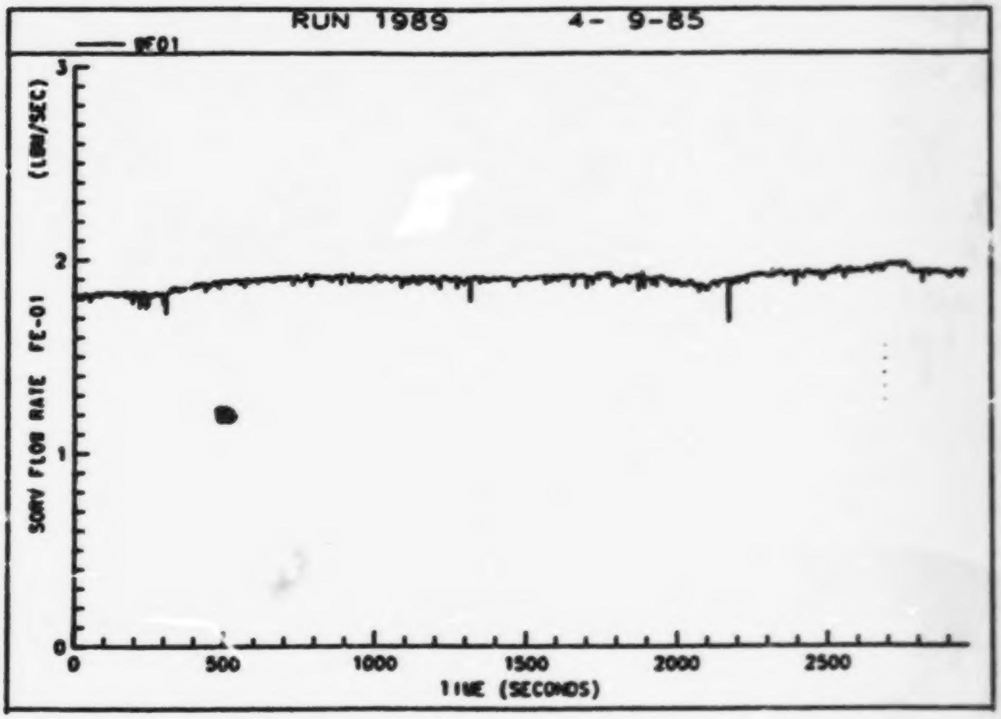

Figure 5-224. SORV Flow Rate (WF-01): Test No. 9 (T-1989)

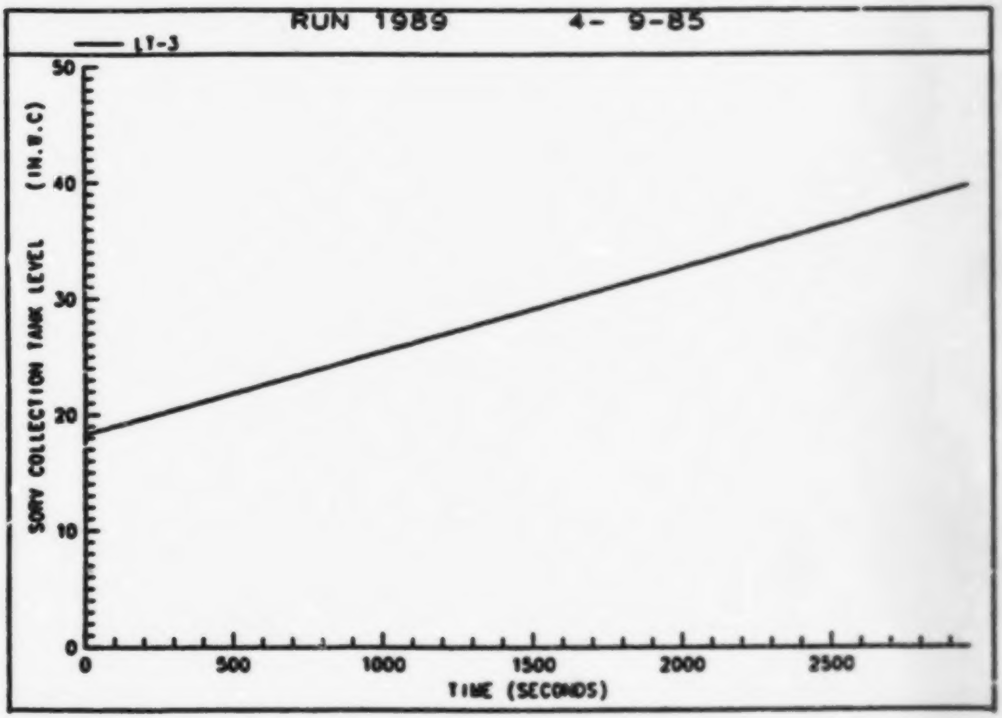

Figure 5-225. SORV Tank Level (LT-3): Test No. 9 (T-1989)

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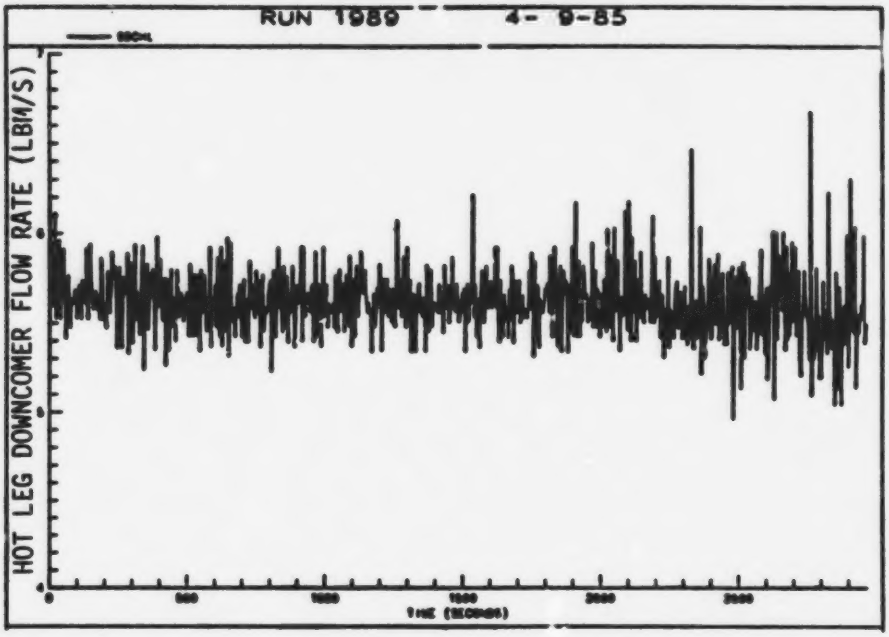

Figure 5-226. Hot Leg Downcomer Flow Rate (WDCHL): Test No. 9 (T-1989)

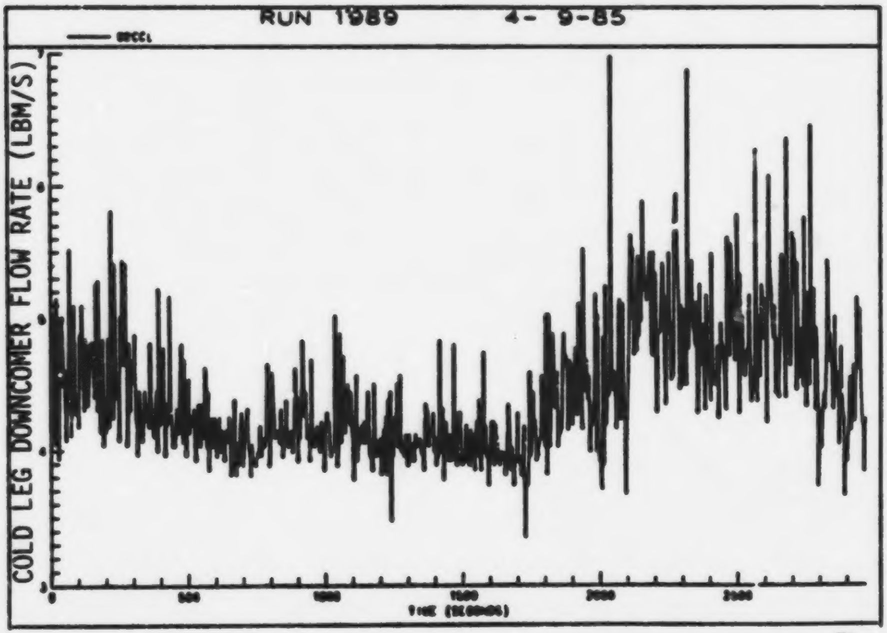

Figure 5-227. Cold Leg Downcomer Flow Rate (WDCCL): Test No. 9 (T-1989)

309

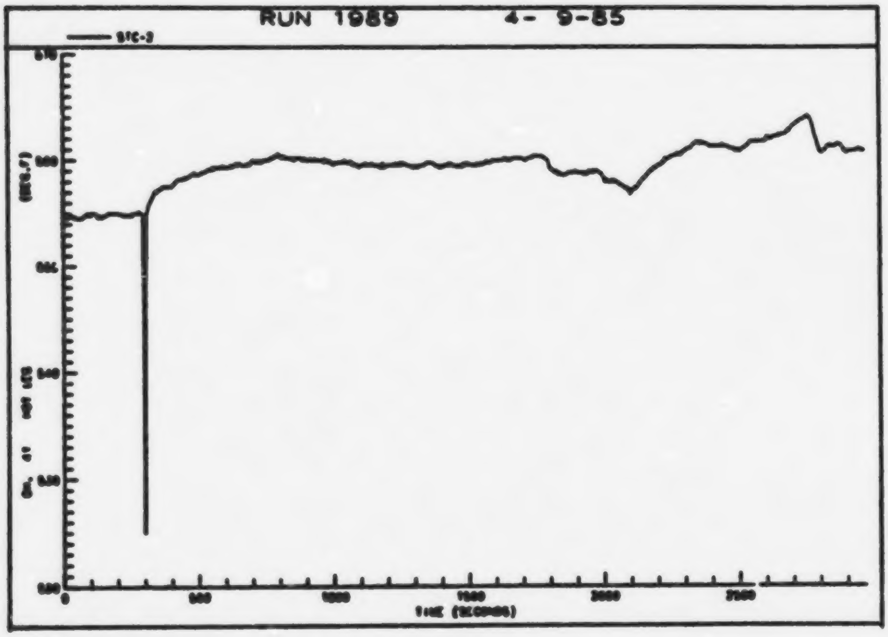

Figure 5-228. Secondary Fluid Temperature (STC-2): Test No. 9 (T-1989)

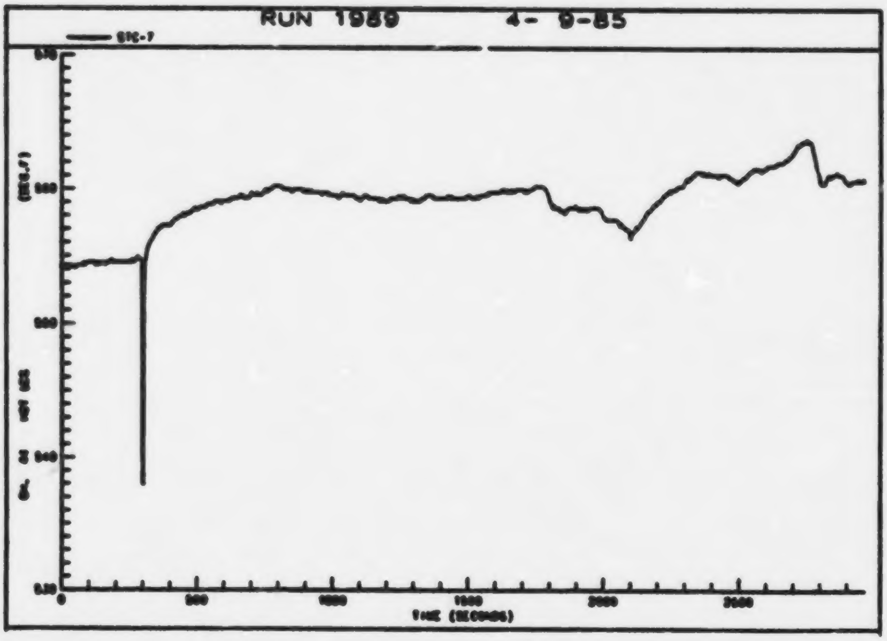

Figure 5-229. Secondary Fluid Temperature (STC-7): Test No. 9 (T-1989)

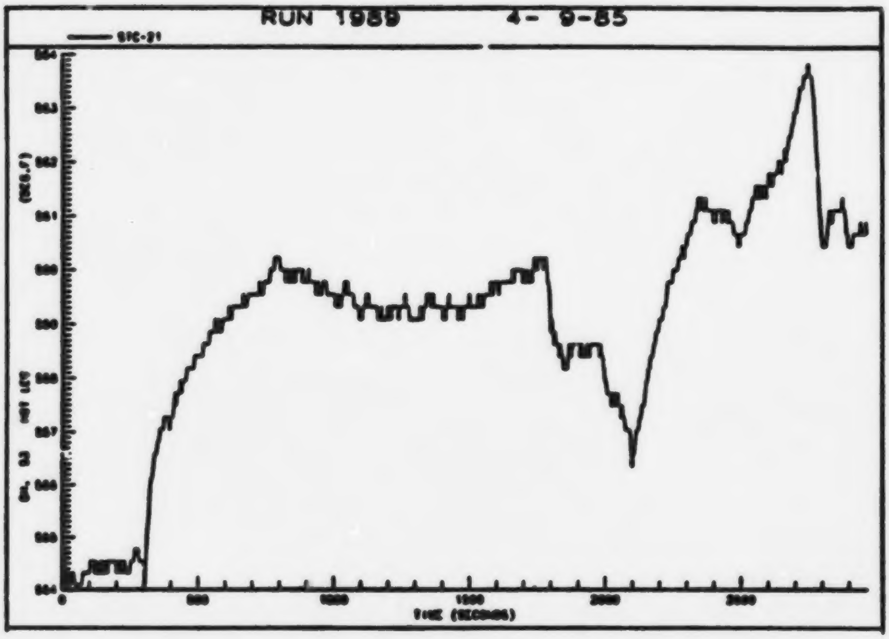

Figure 5-230. Secondary Fluid Temperature (STC-21): Test No. 9 (T-1989)

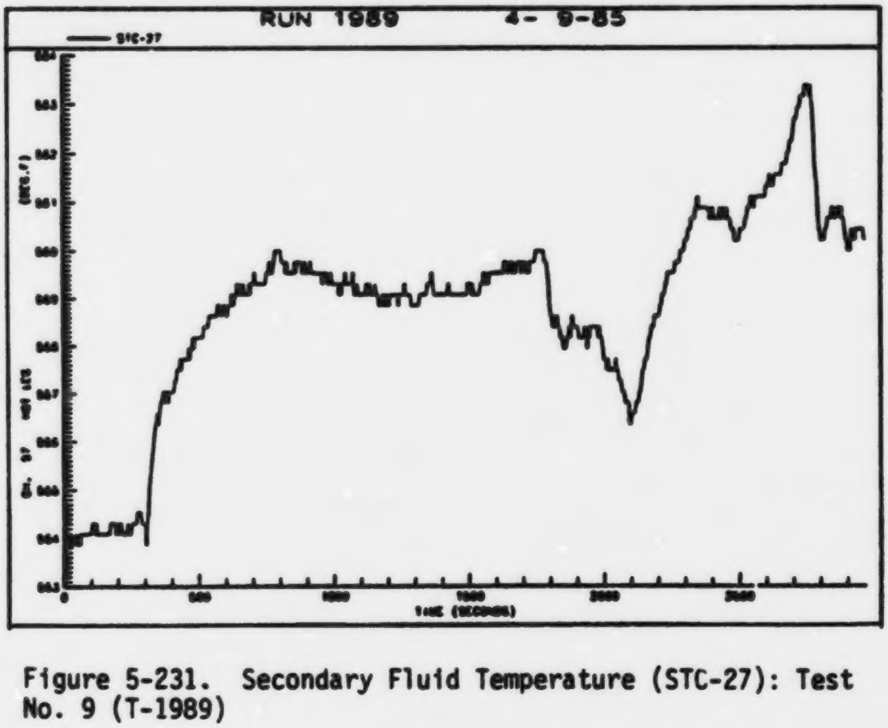

Figure 5-231. Secondary Fluid Temperature (STC-27): Test No. 9 (T-1989)

311

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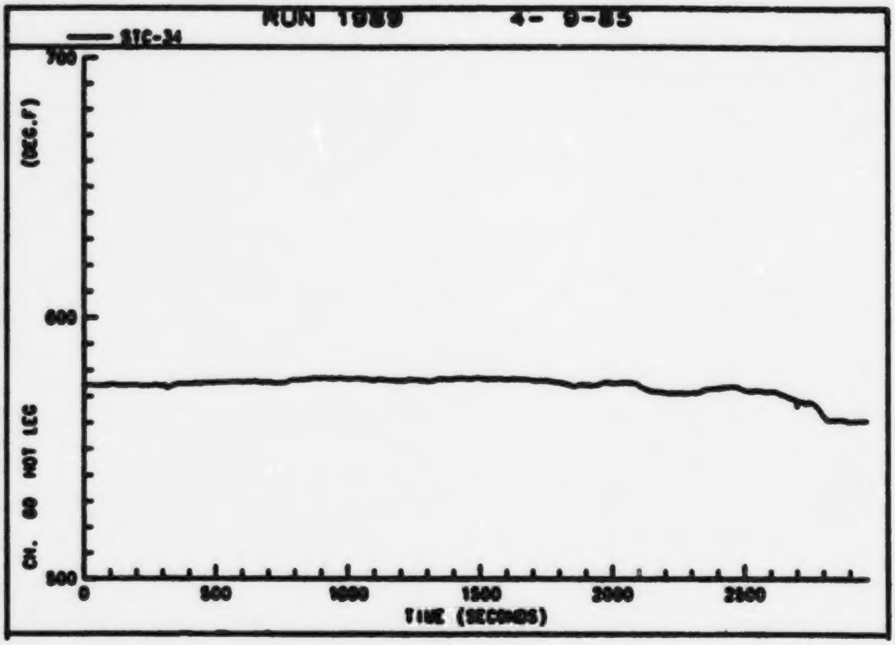

Figure 5-232. Secondary Fluid Temperature (STC-34): Test No. 9 (T-1989)

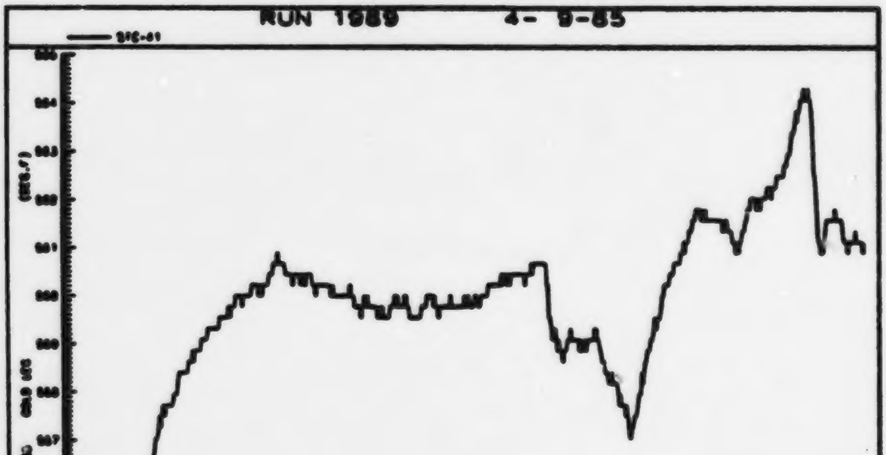

Figure 5-233. Secondary Fluid Temperature (STC-41): Test No. 9 (T-1989)

312

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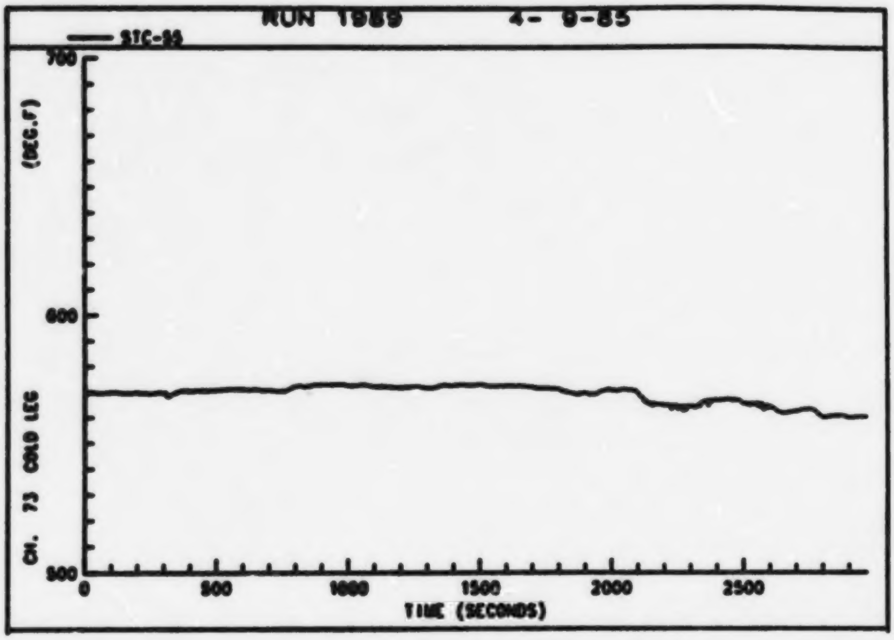

Figure 5-234. Secondary Fluid Temperature (STC-55): Test No. 9 (T-1989)

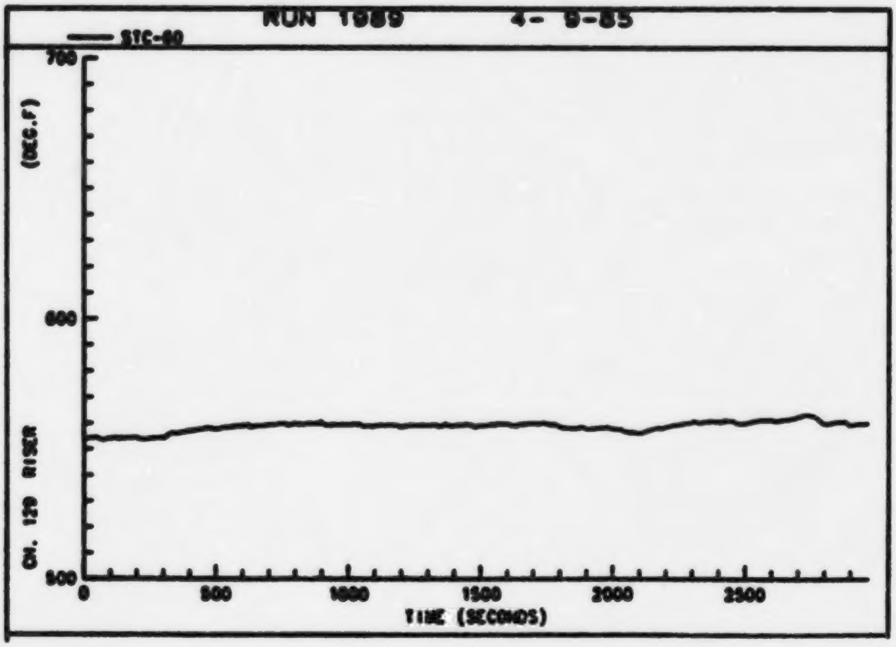

Figure 5-235. Secondary Fluid Temperature (STC-60): Test No. 9 (T-1989)

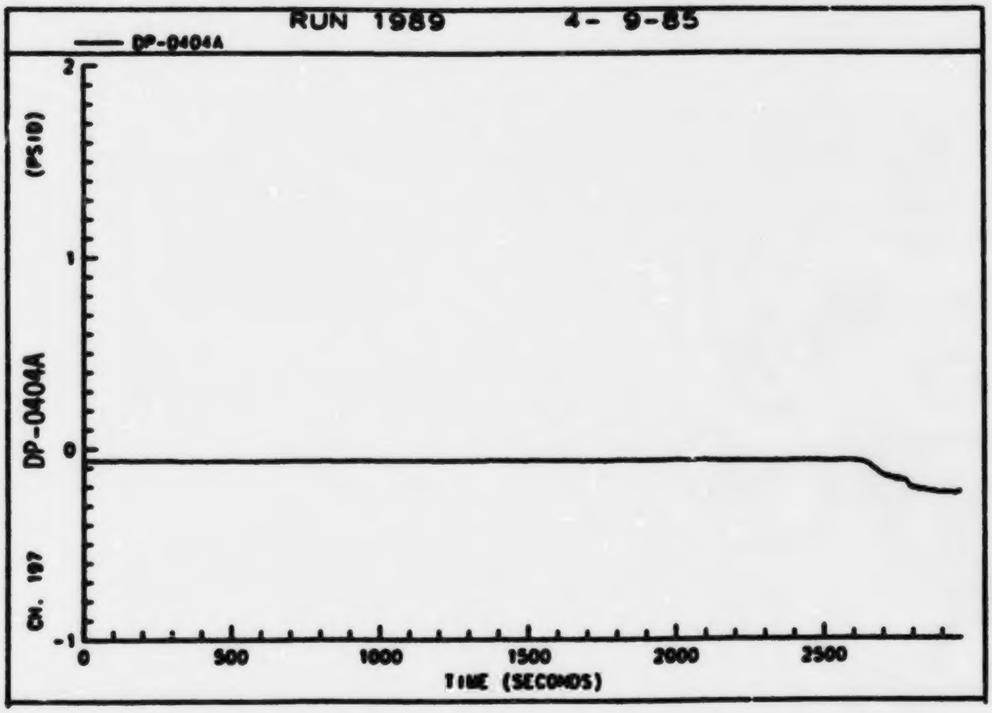

Figure 5-236. Differential Pressure, DP-0404A: Test No. 9 (T-1989)

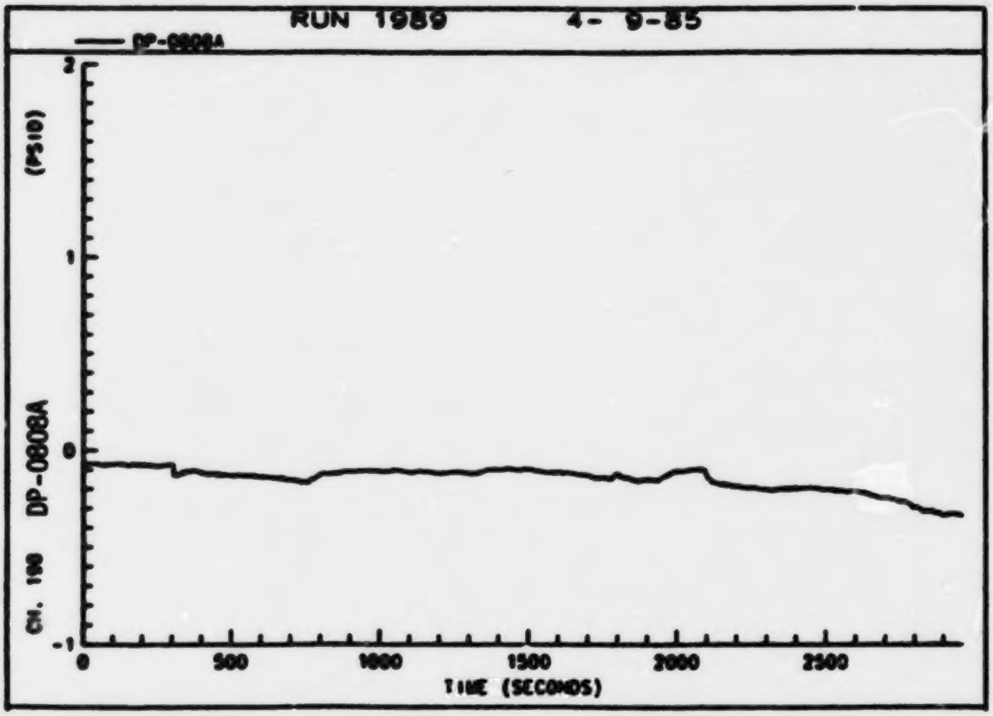

Figure 5-237. Differential Pressure, DP-0808A: Test No. 9 (T-1989)

314

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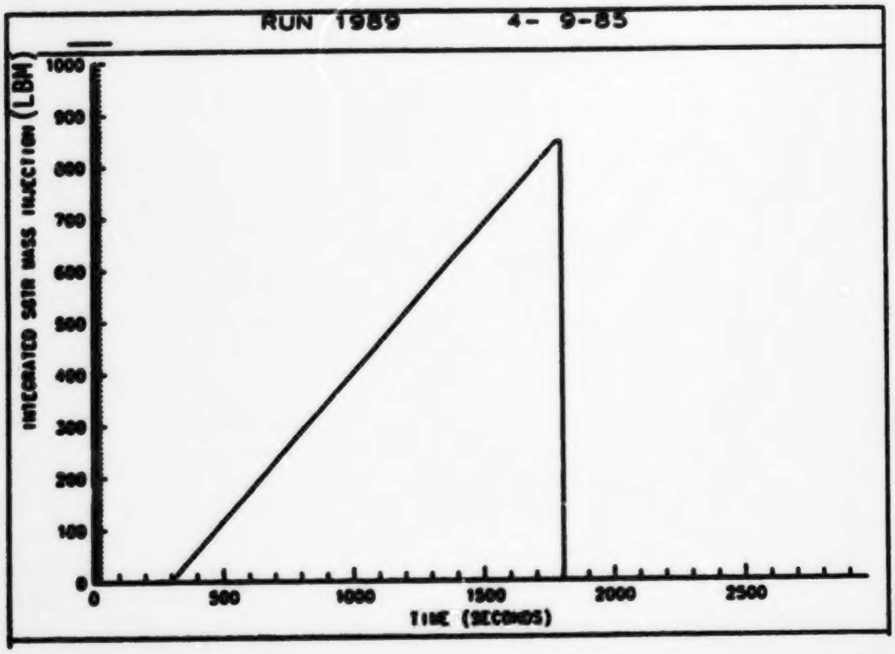

Figure 5-238. Integrated SGTR Flow: Test No. 9 (T-1989)

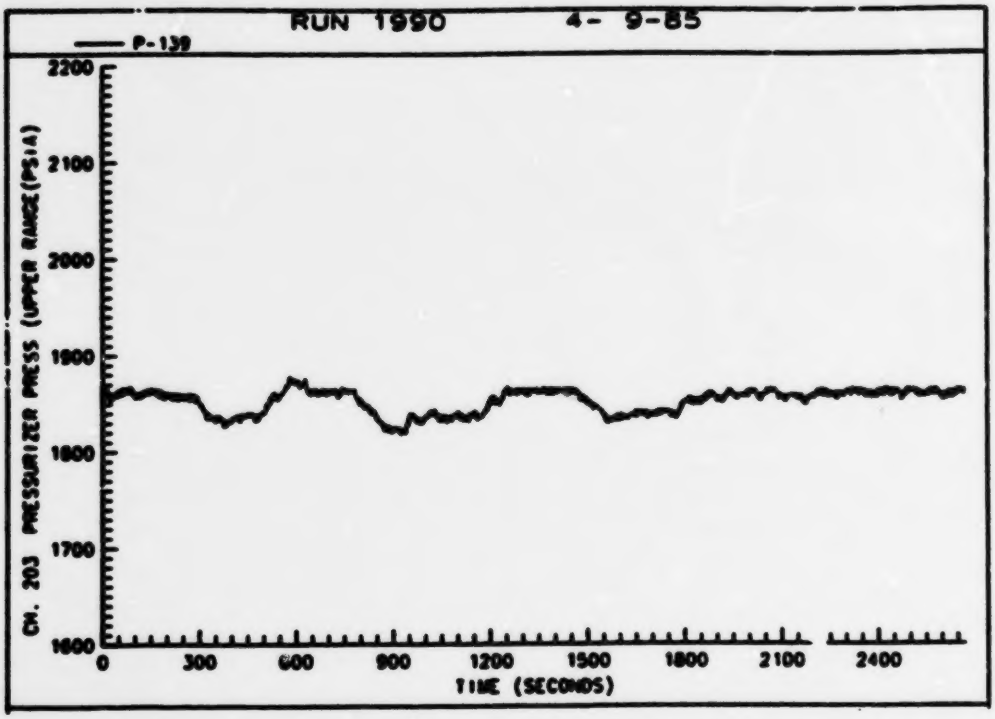

Figure 5-239. Primary System (Pressurizer) Pressure (P-139): Test No. 9 (T-1990)

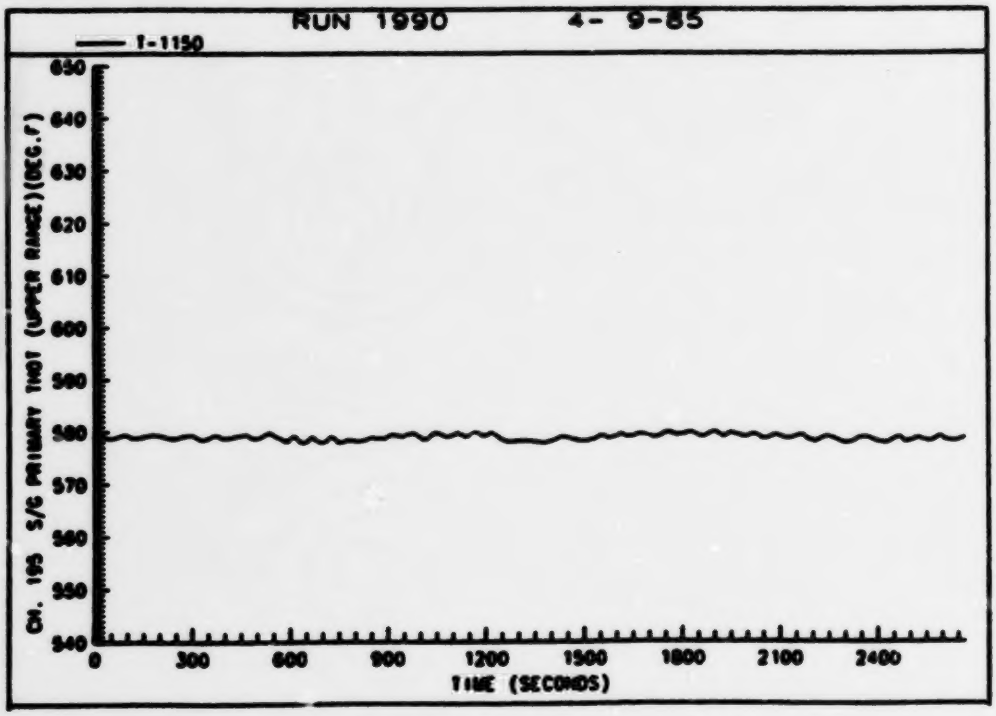

Figure 5-240. Primary Fluid T_{hot} (T-1150): Test No. 9 (T-1990)

316

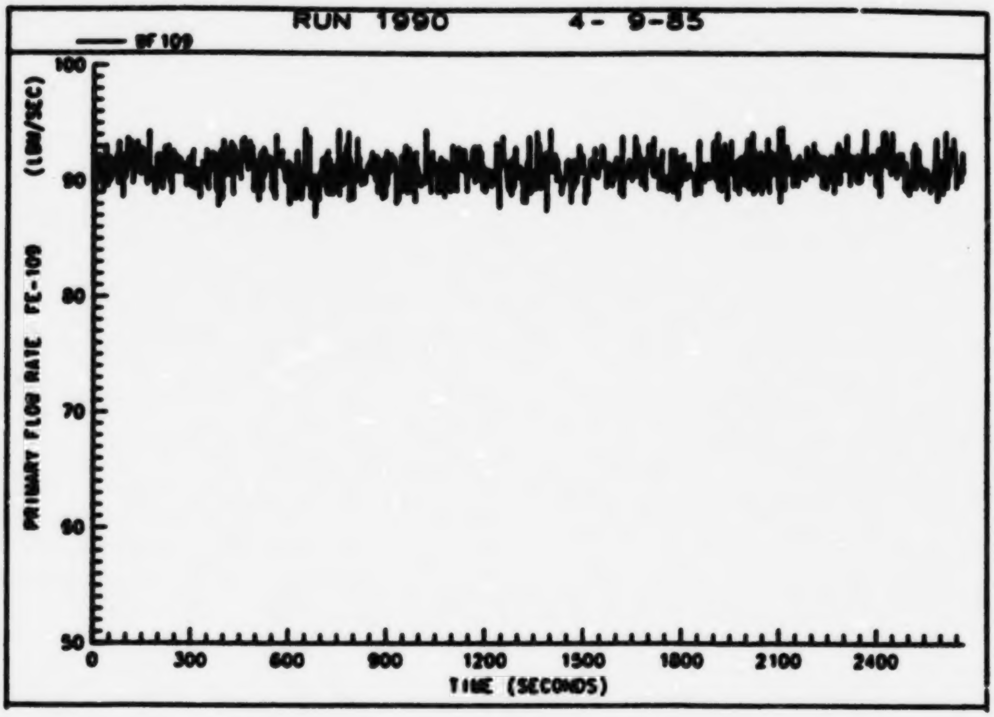

Figure 5-241. Primary Fluid Flow Rate (WF-109): Test No. 9 (T-1990)

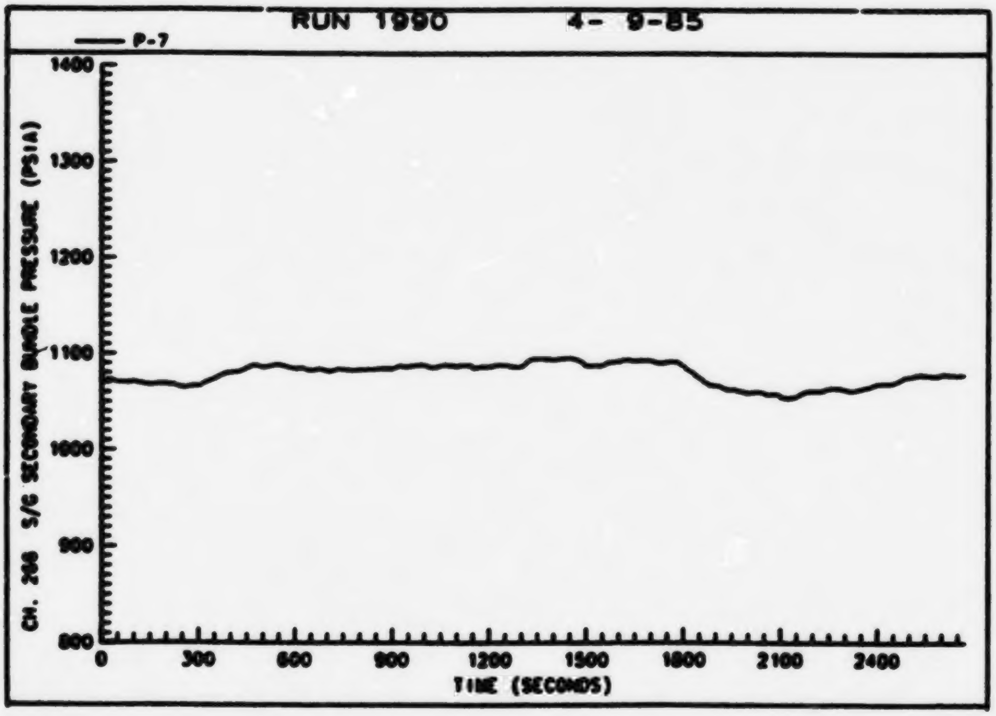

Figure 5-242. Secondary Side Pressure (P-7): Test No. 9 (T-1990)

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317

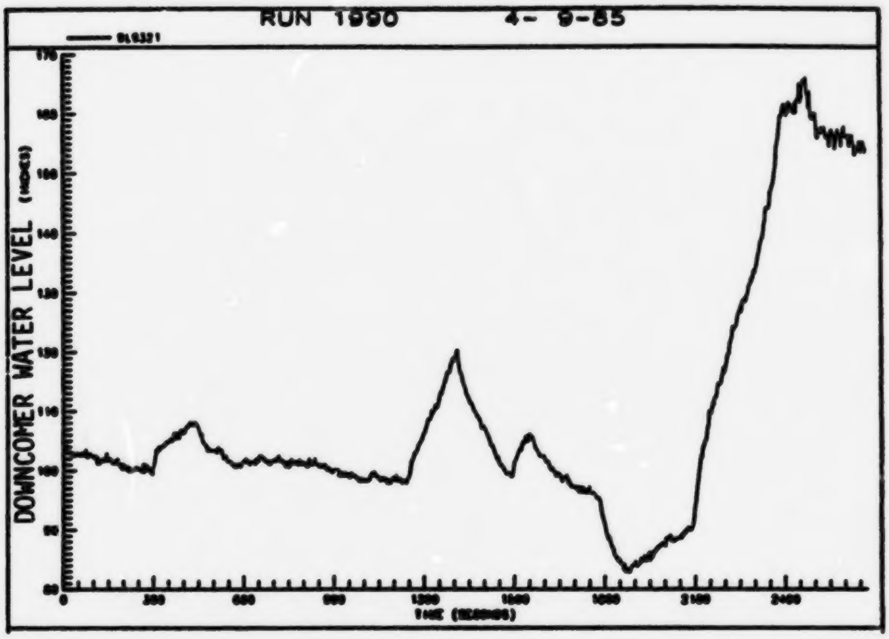

Figure 5-243. Downcomer Water Level - Wide Range (WL-9321): Test No. 9 (T-1990)

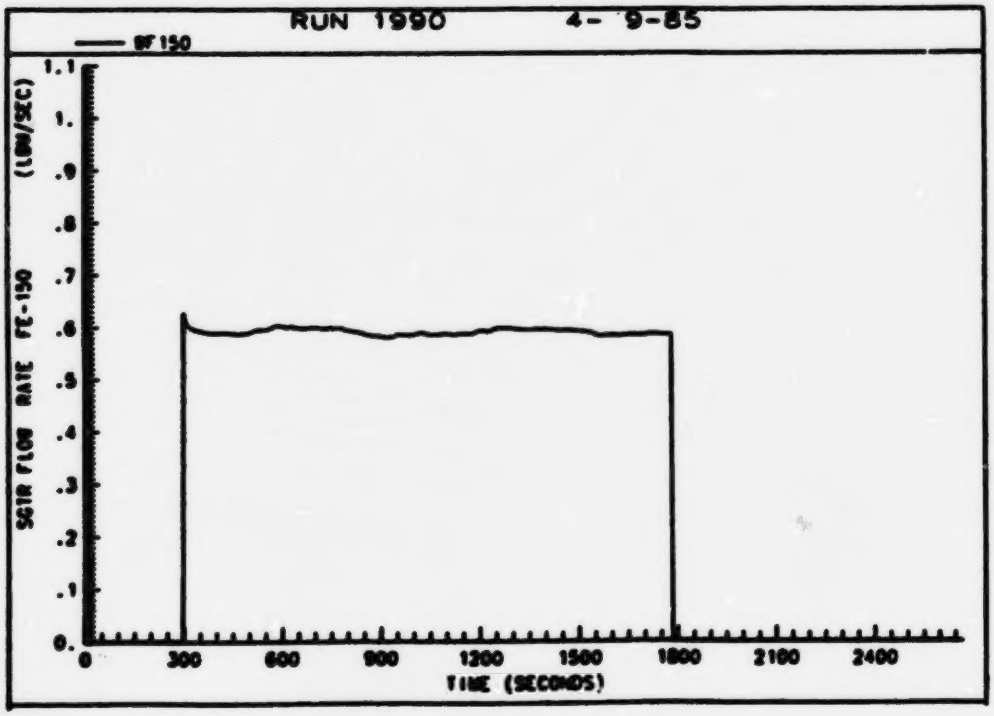

Figure 5-244. SGTR Flow Rate (WF-150): Test No. 9 (T-1990)

318

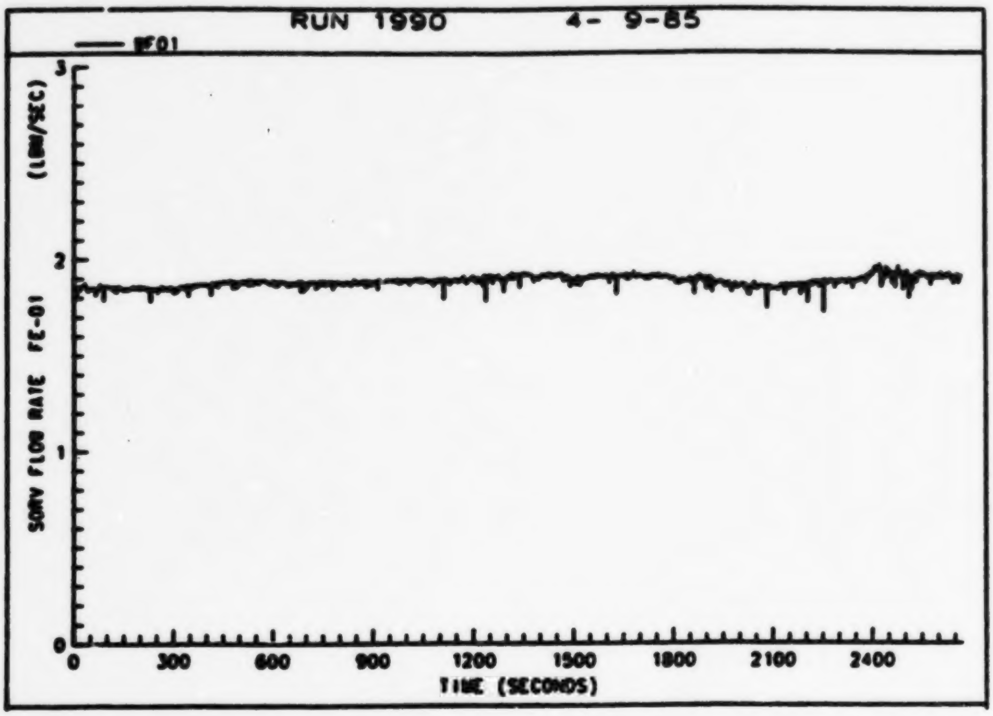

Figure 5-245. SORV Flow Rate (WF-01): Test No. 9 (T-1990)

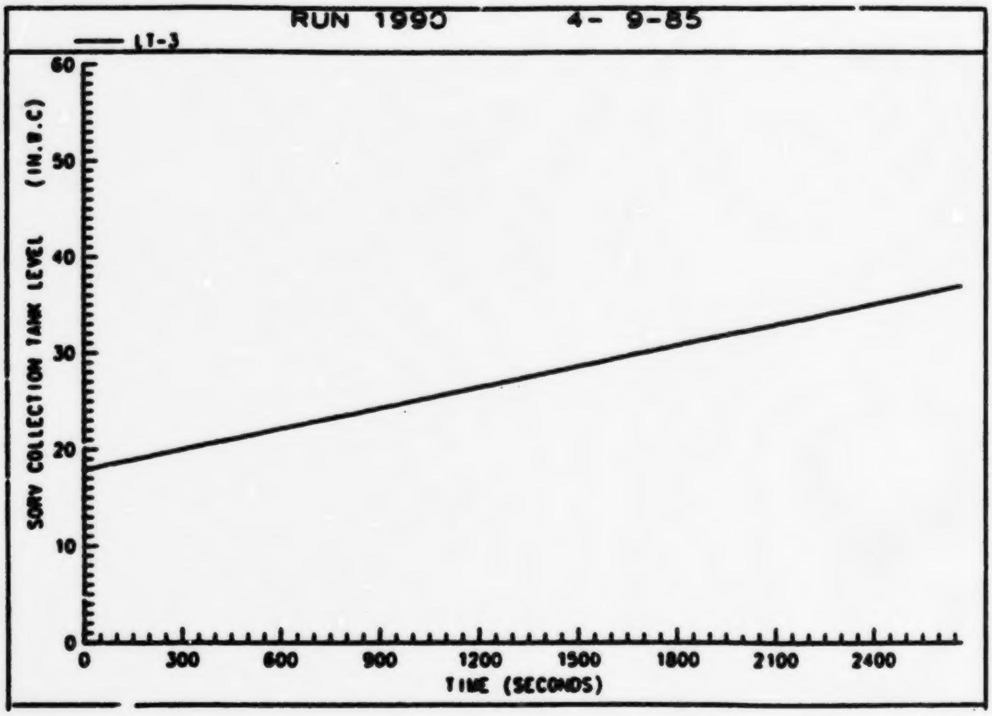

Figure 5-246. SORV Tank Level (LT-3): Test No. 9 (T-1990)

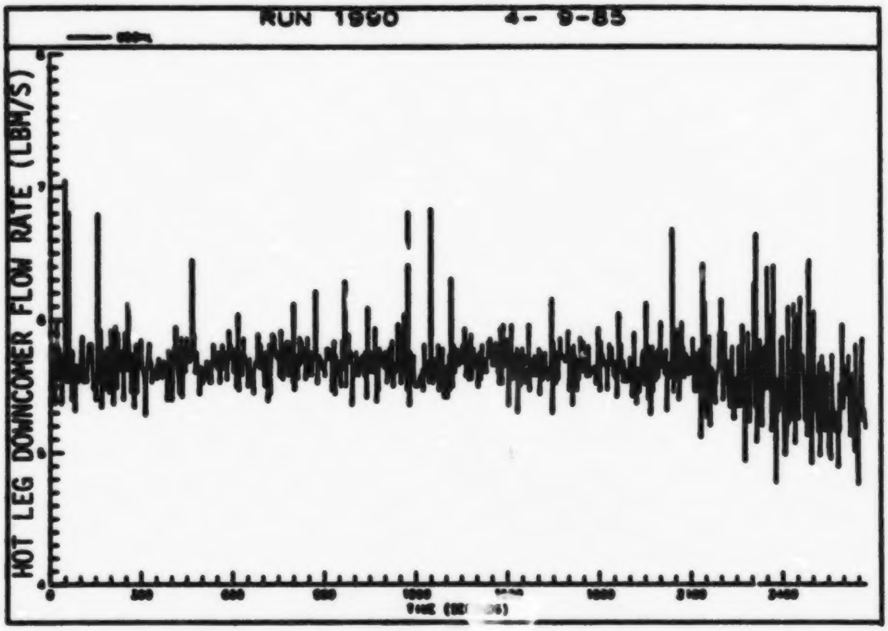

Figure 5-247. Hot Leg Downcomer Flow Rate (WDCHL): Test No. 9 (T-1990)

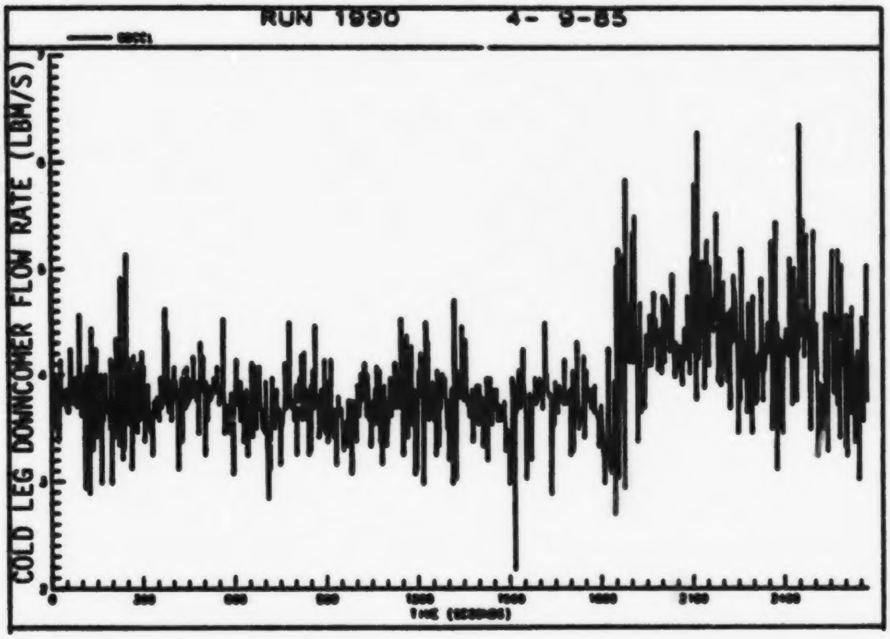

Figure 5-248. Cold Leg Downcomer Flow Rate (WDCCL): Test No. 9 (T-1990)

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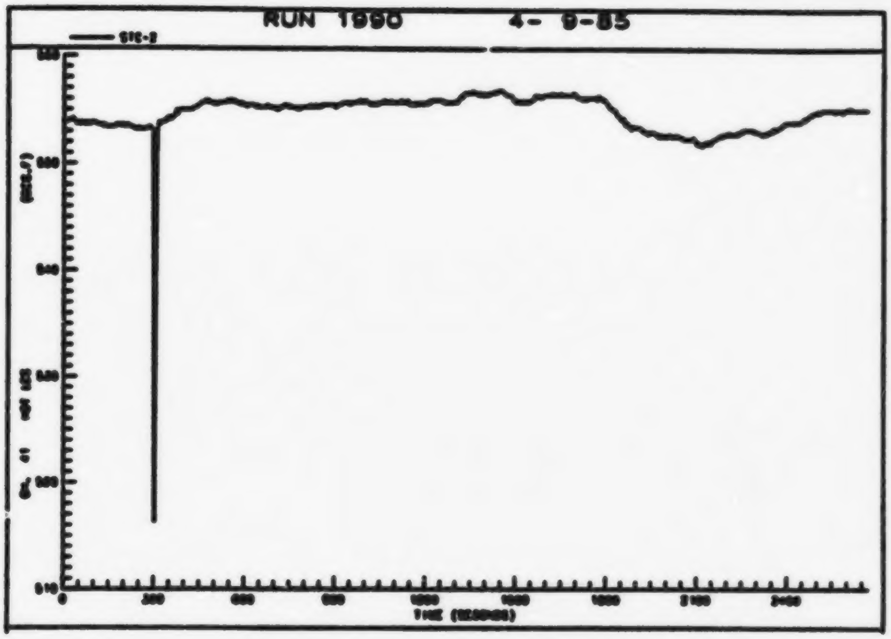

Figure 5-249. Secondary Fluid Temperature (STC-2): Test No. 9 (T-1990)

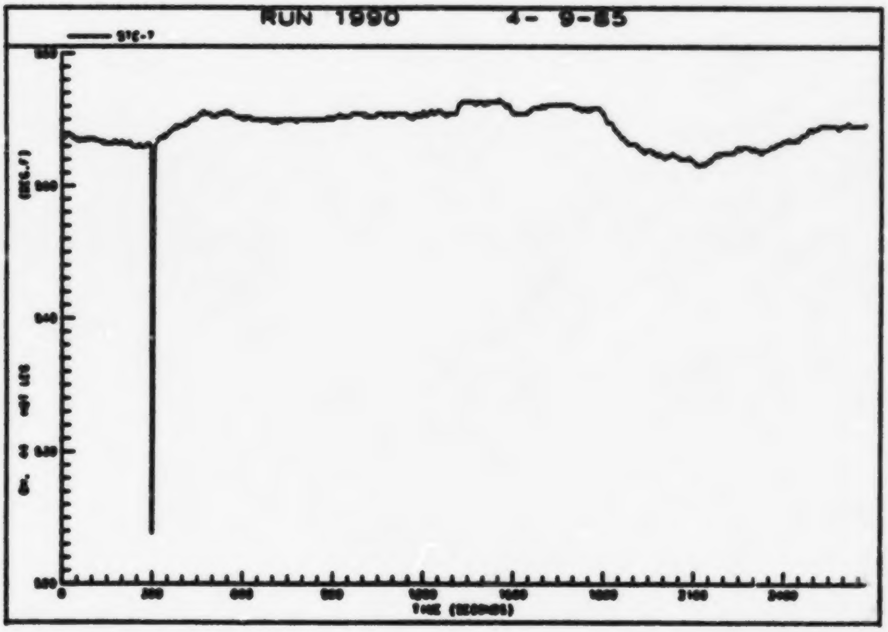

Figure 5-250. Secondary Fluid Temperature (STC-7): Test No. 9 (T-1990)

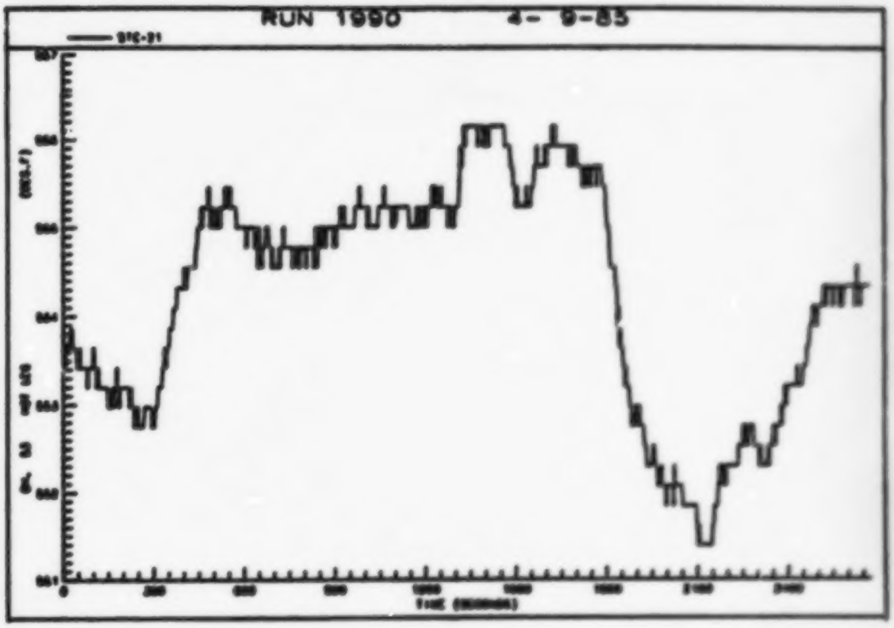

Figure 5-251. Secondary Fluid Temperature (STC-21): Test No. 9 (T-1990)

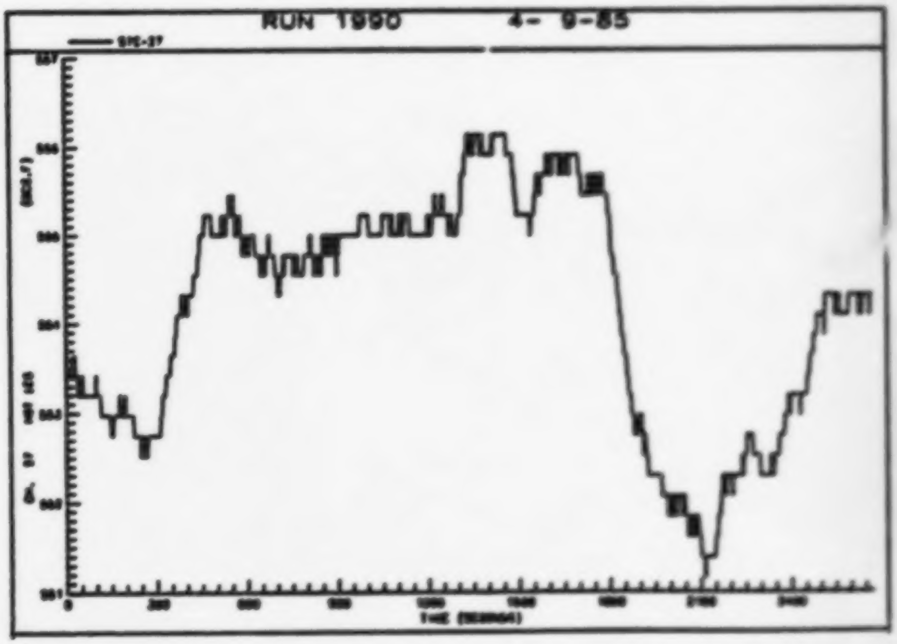

Figure 5-252. Secondary Fluid Temperature (STC-27): Test No. 9 (T-1990)

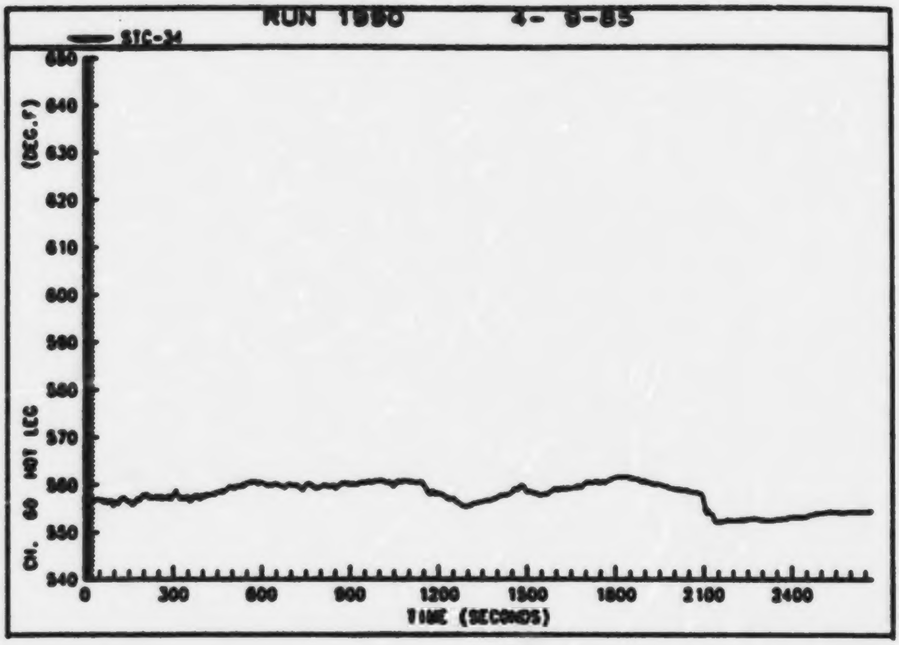

Figure 5-253. Secondary Fluid Temperature (STC-34): Test No. 9 (T-1990)

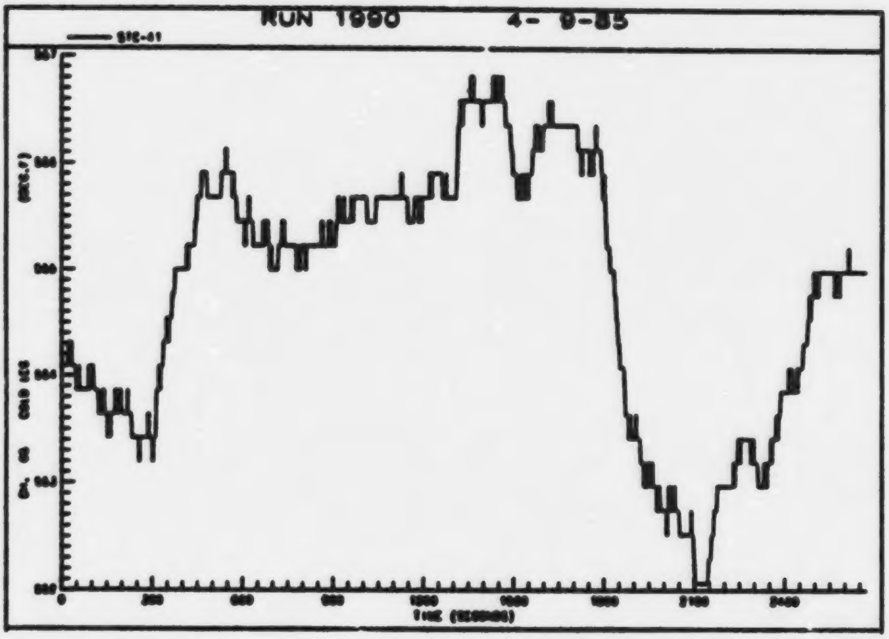

Figure 5-254. Secondary Fluid Temperature (STC-41): Test No. 9 (T-1990)

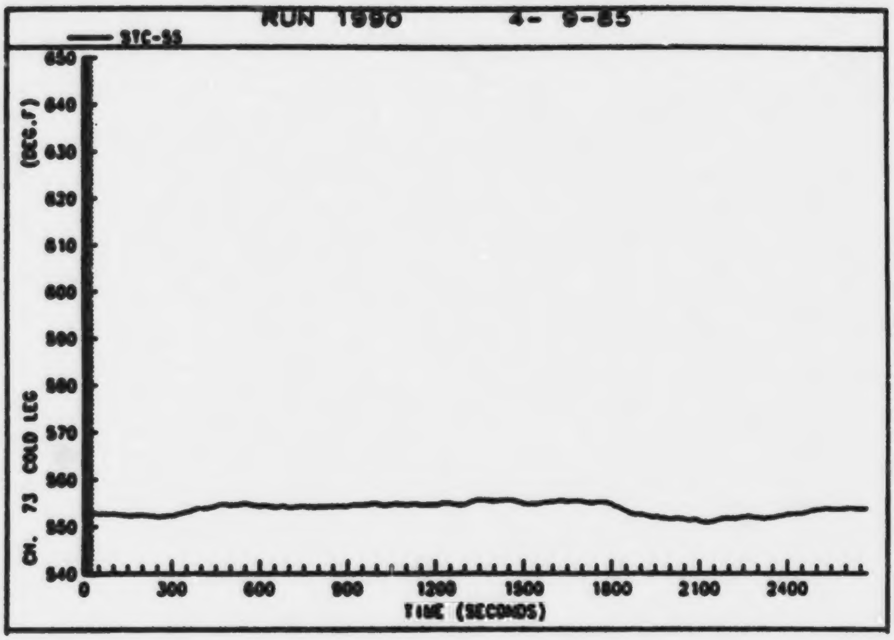

Figure 5-255. Secondary Fluid Temperature (STC-55): Test No. 9 (T-1990)

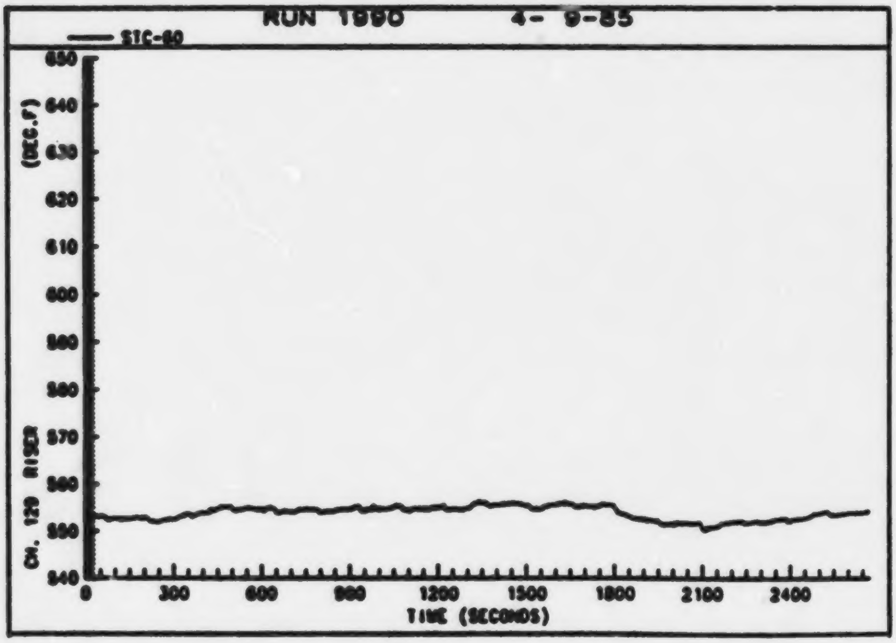

Figure 5-256. Secondary Fluid Temperature (STC-60): Test No. 9 (T-1990)

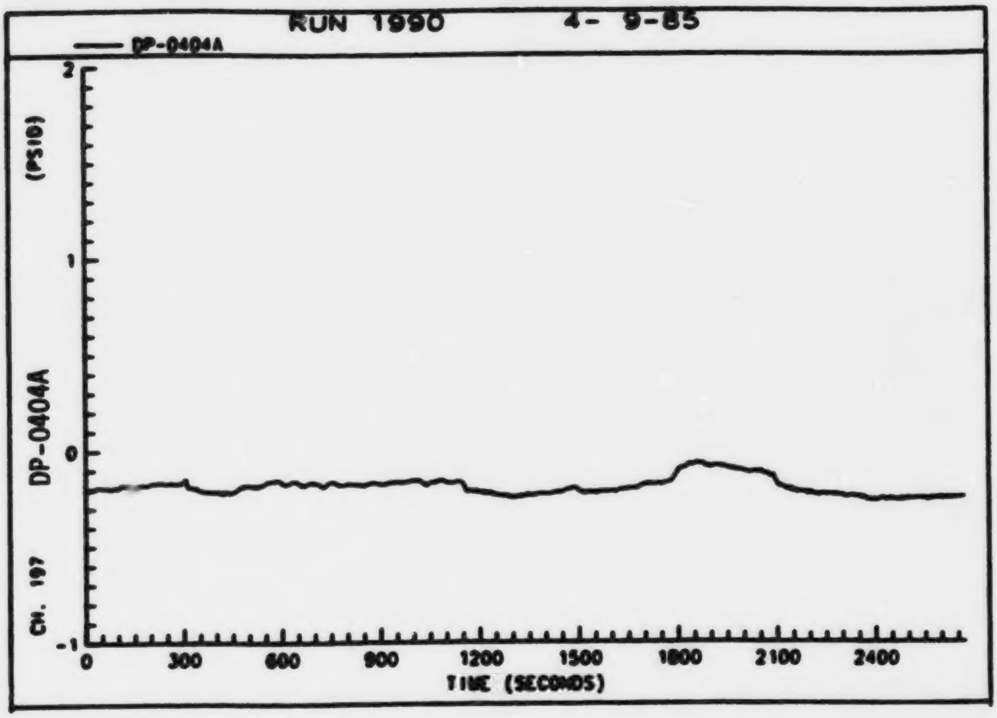

Figure 5-257. Differential Pressure, DP-0404A: Test No. 9 (T-1990)

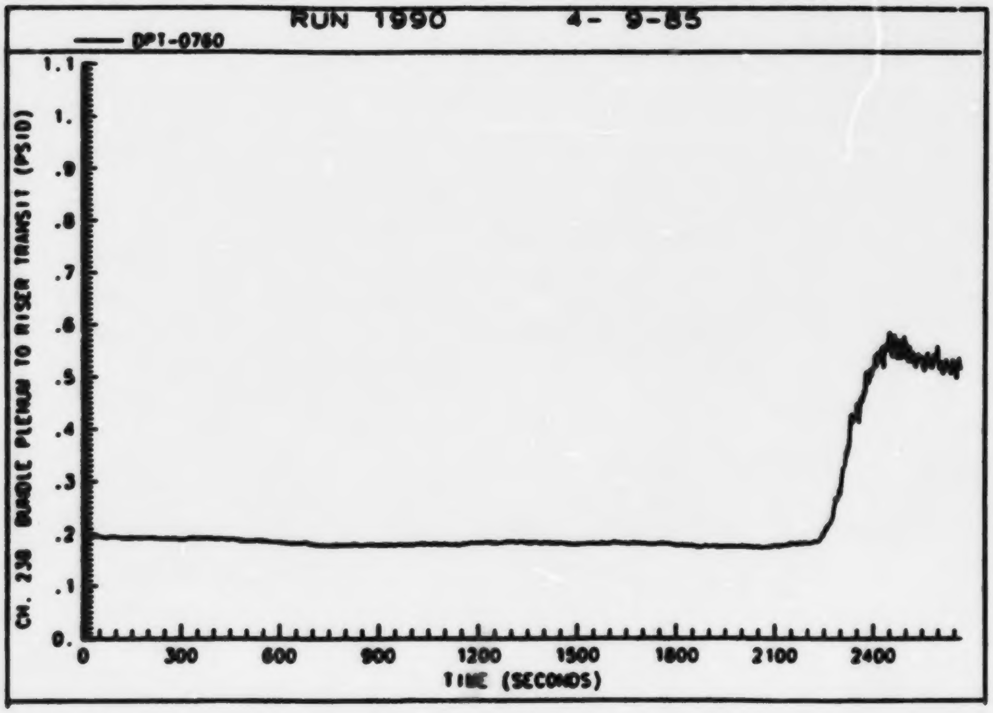

Figure 5-258. Differential Pressure DP-0760: Test No. 9 (T-1990)

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325

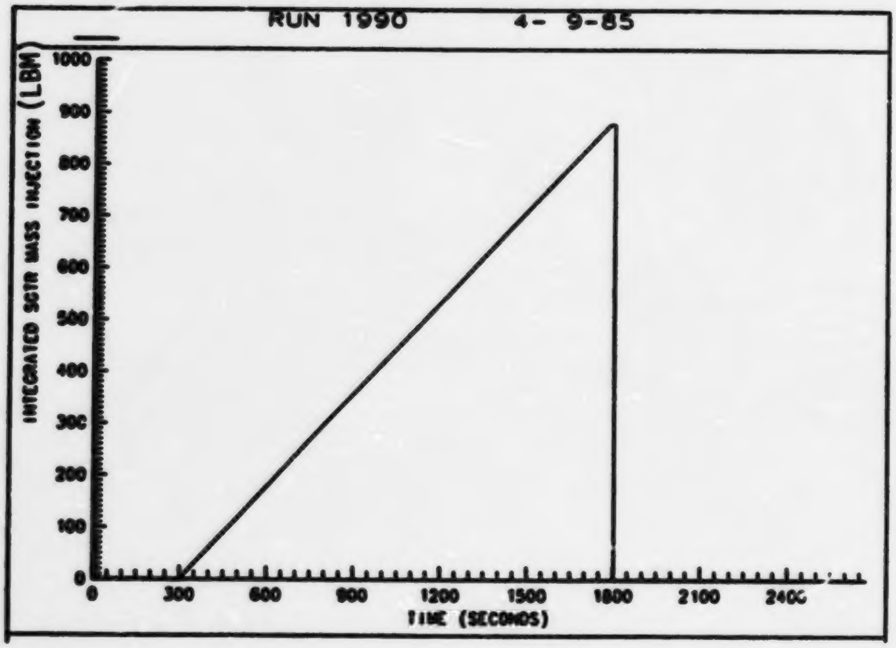

Figure 5-259. Integrated SGTR Flow: Test No. 9 (T-1990)

326

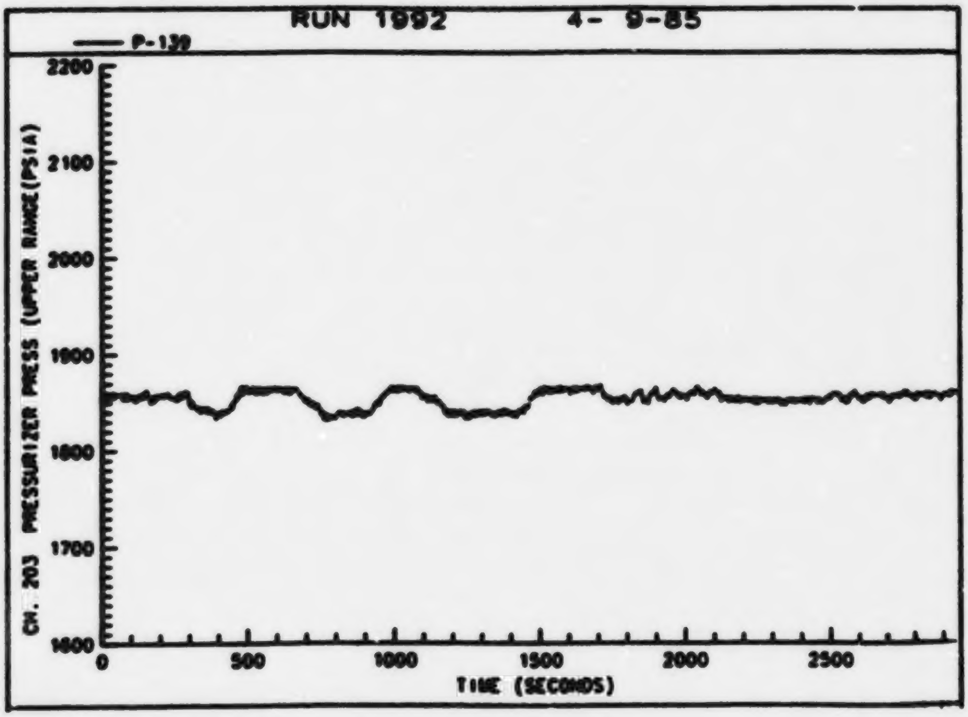

Figure 5-260. Primary System (Pressurizer) Pressure (P-139): Test No. 9 (T-1992)

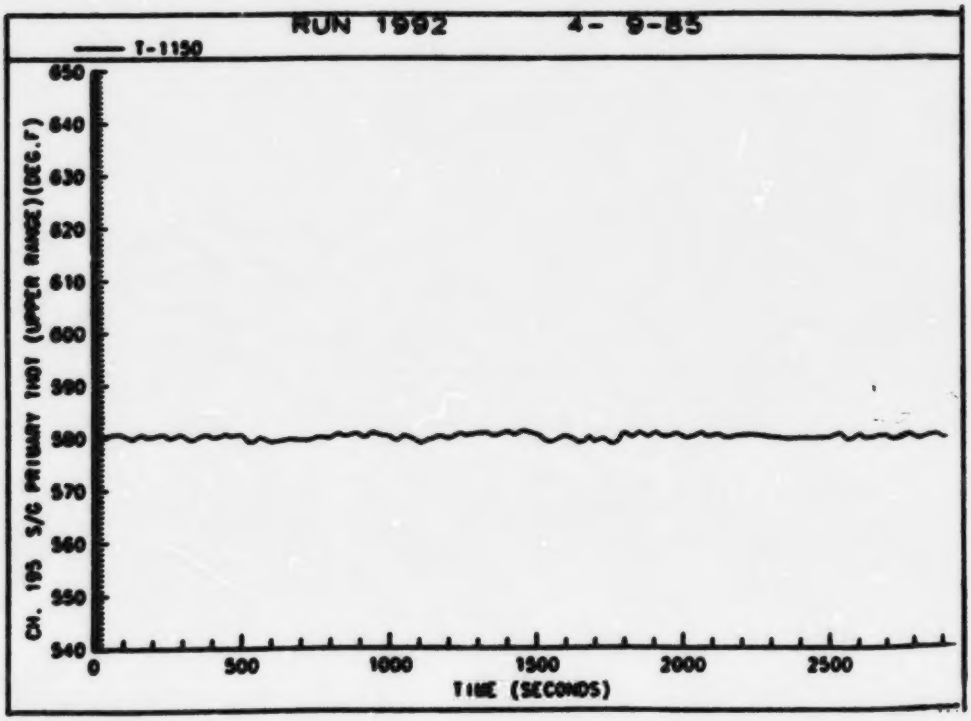

Figure 5-261. Primary Fluid T_{hot} (T-1150): Test No. 9 (T-1992)

327

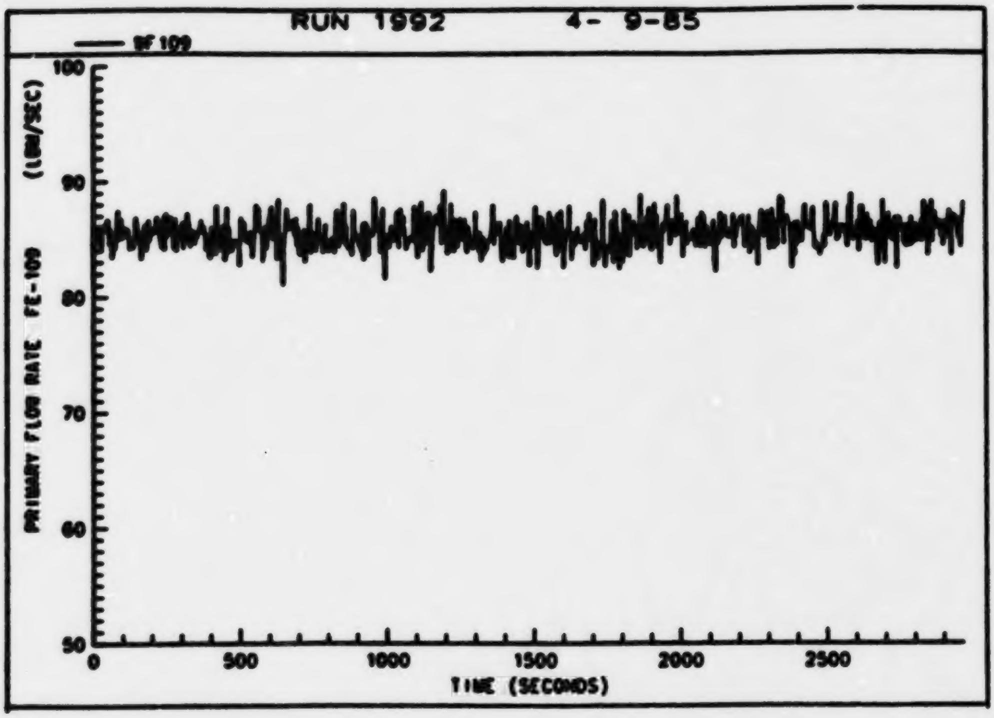

Figure 5-262. Primary Fluid Flow Rate (WF-109): Test No. 9 (T-1992)

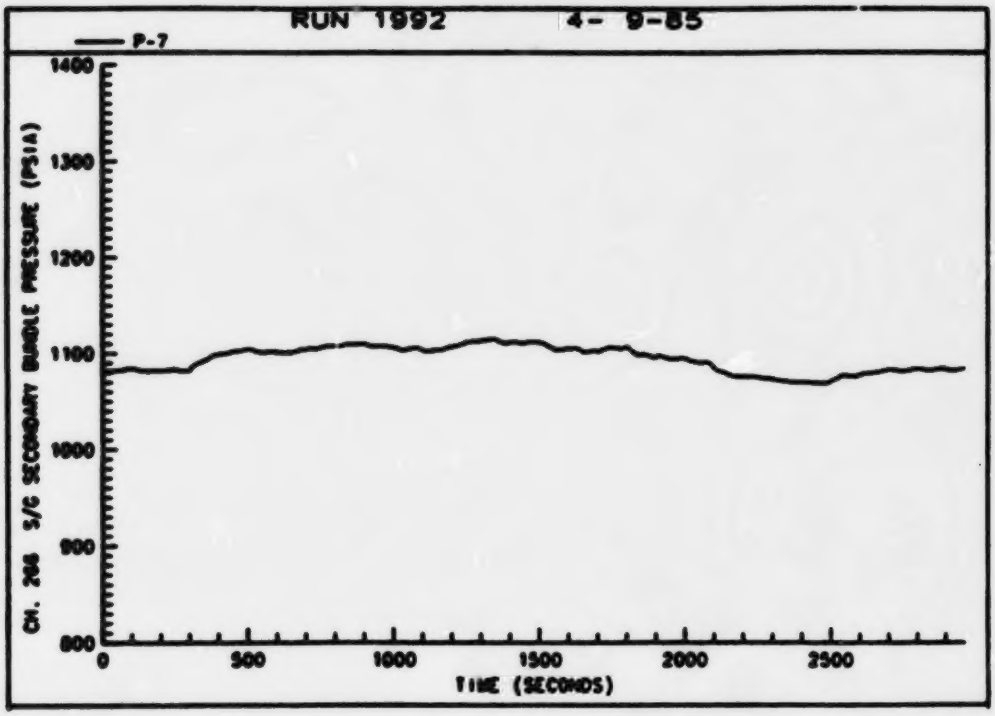

Figure 5-263. Secondary Side Pressure (P-7): Test No. 9 (T-1992)

328

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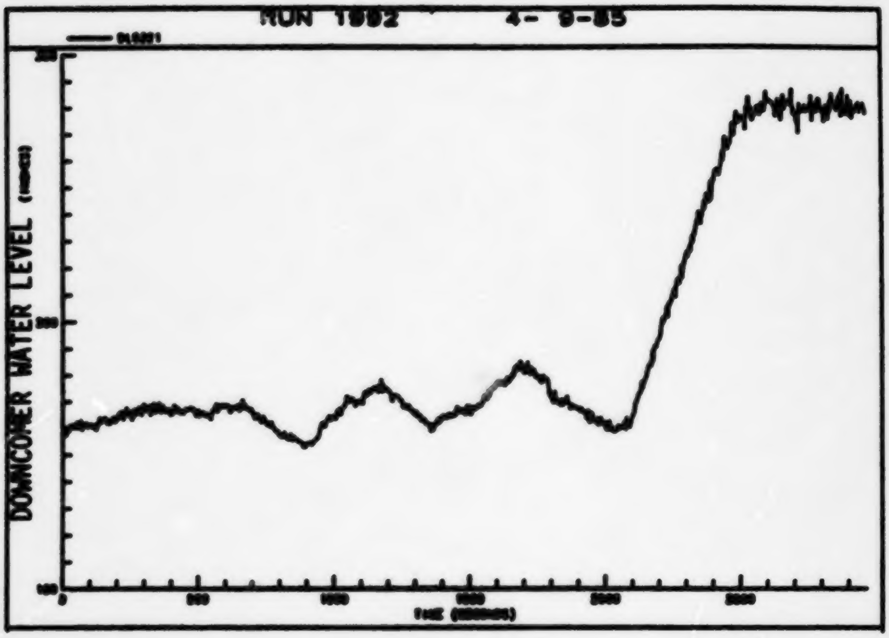

Figure 5-264. Downcomer Water Level - Wide Range (WL-9321): Test No. 9 (T-1992)

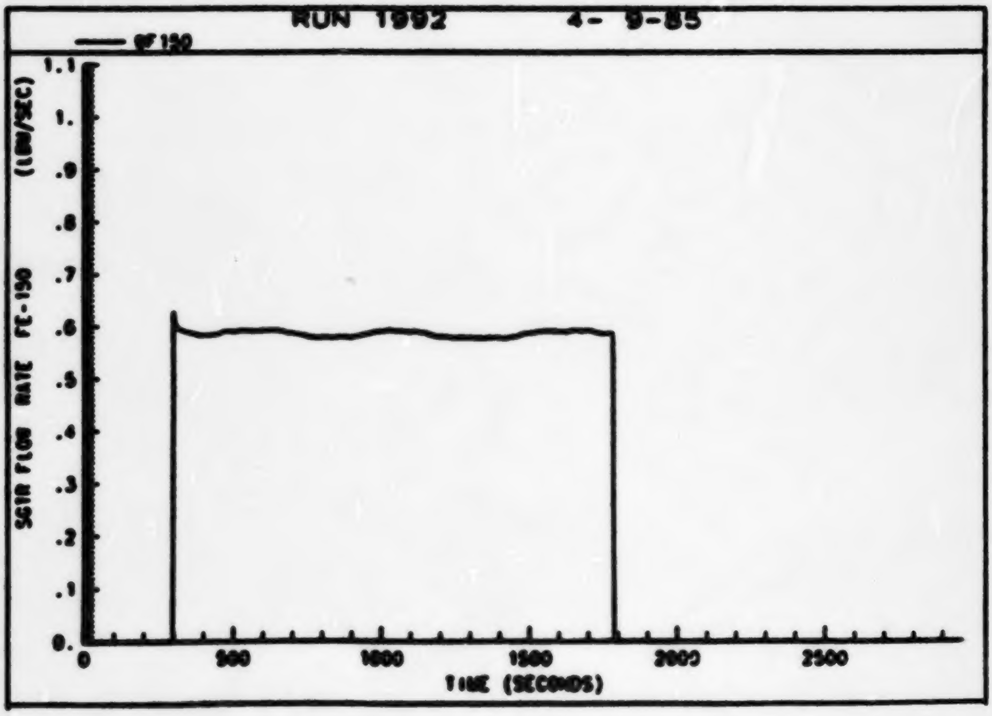

Figure 5-265. SGTR Flow Rate (WF-150): Test No. 9 (T-1992)

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329

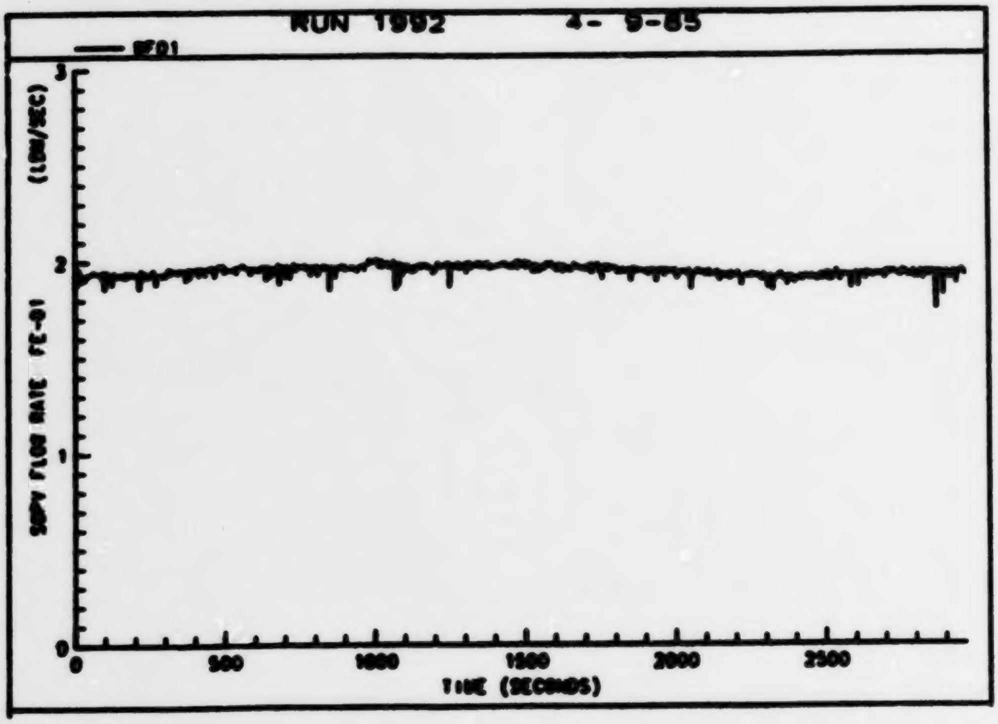

Figure 5-266. SORV Flow Rate (WF-01): Test No. 9 (T-1992)

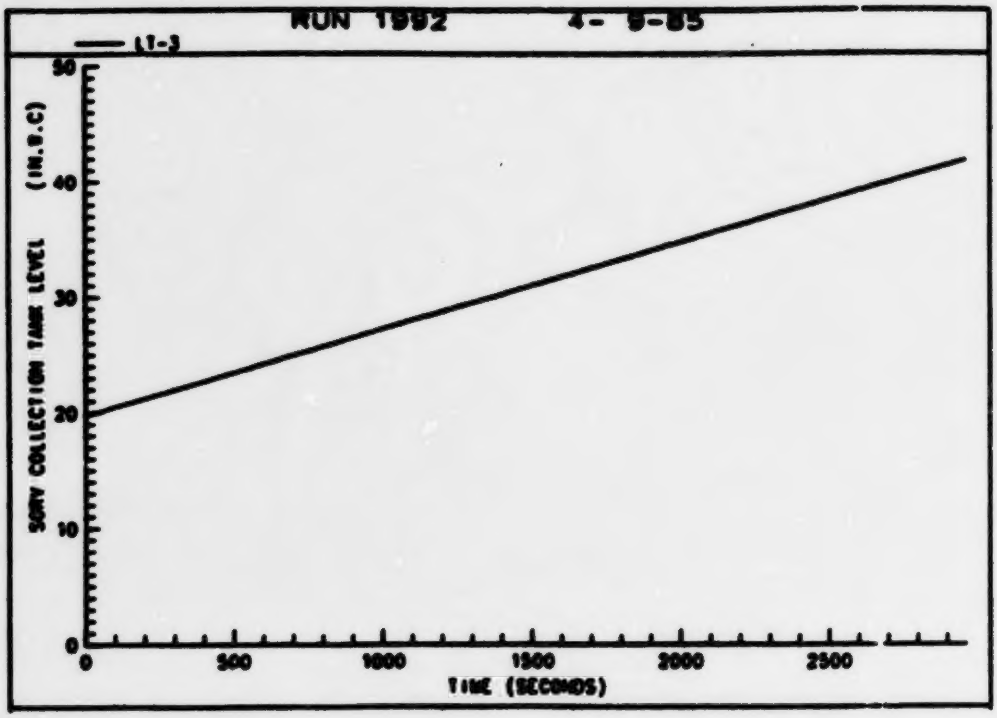

Figure 5-267. SORV Tank Level (LT-3): Test No. 9 (T-1992)

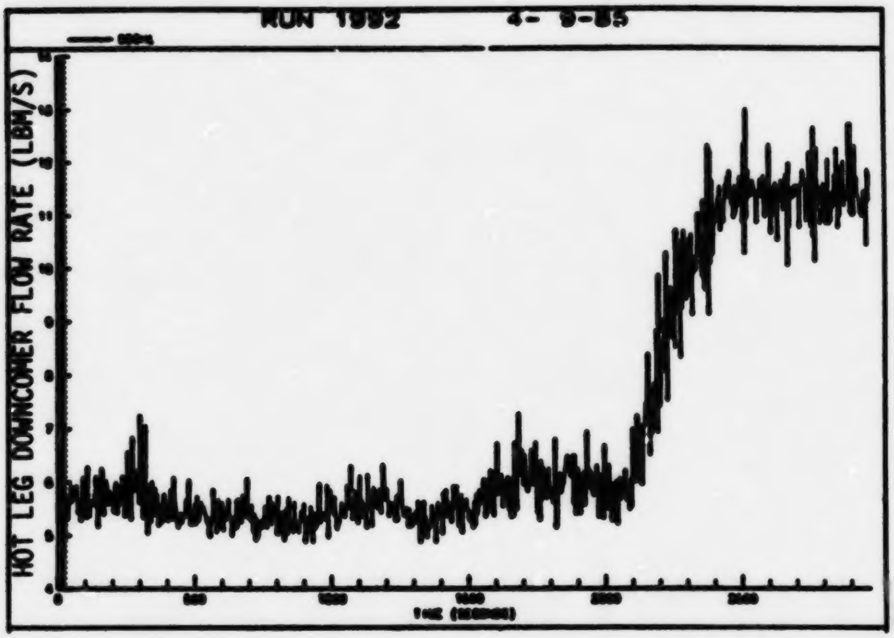

Figure 5-268. Hot Leg Downcomer Flow Rate (WDCHL): Test No. 9 (T-1992)

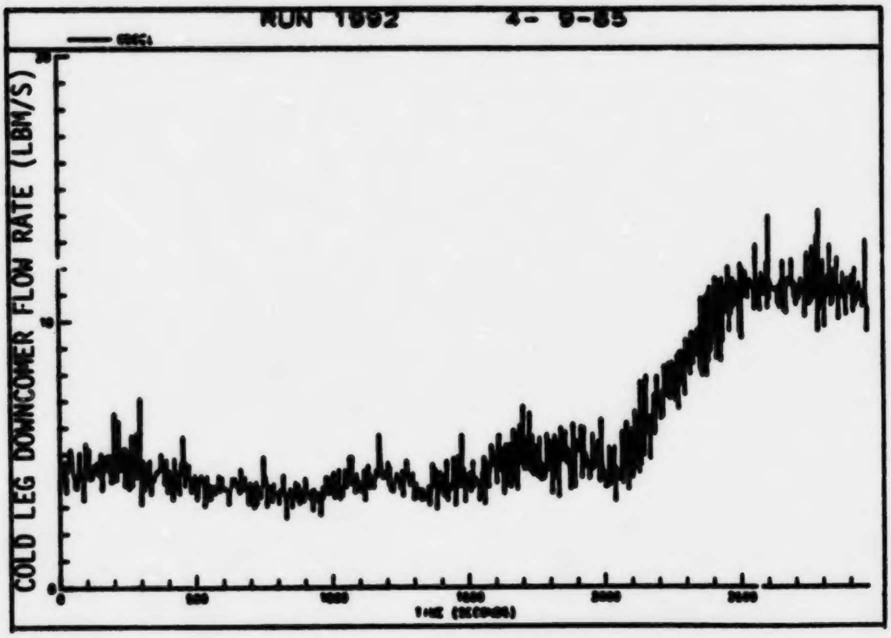

Figure 5-269. Cold Leg Downcomer Flow Rate (WDCCL): Test No. 9 (T-1992)

331

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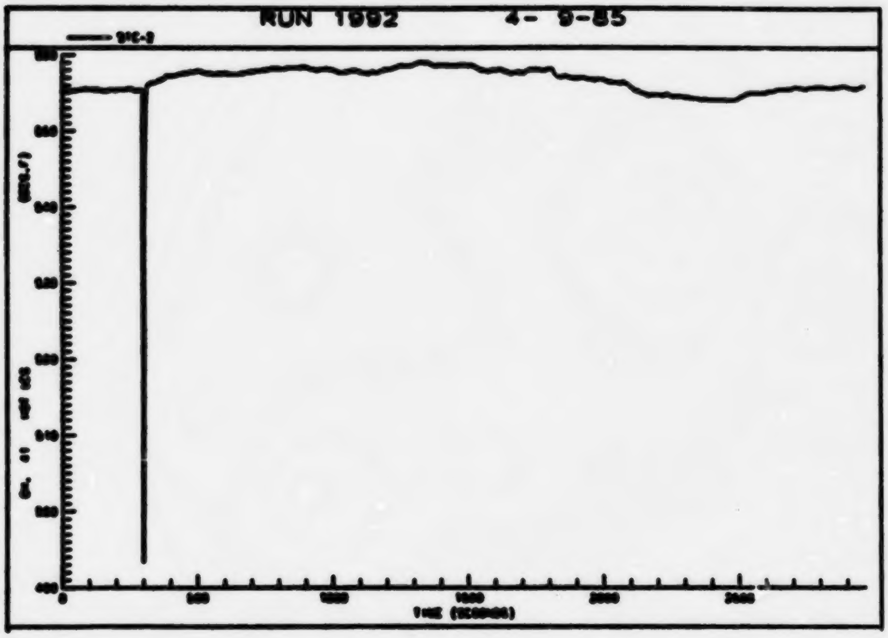

Figure 5-270. Secondary Fluid Temperature (STC-2): Test No. 9 (T-1992)

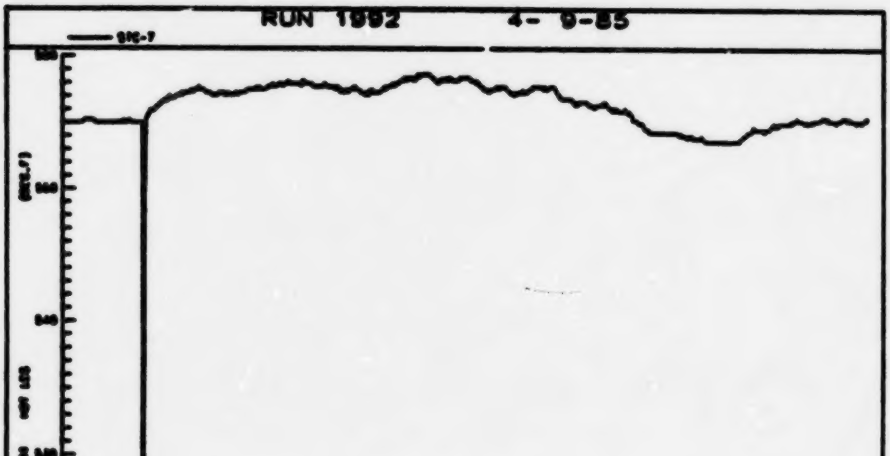

Figure 5-271. Secondary Fluid Temperature (STC-7): Test No. 9 (T-1992)

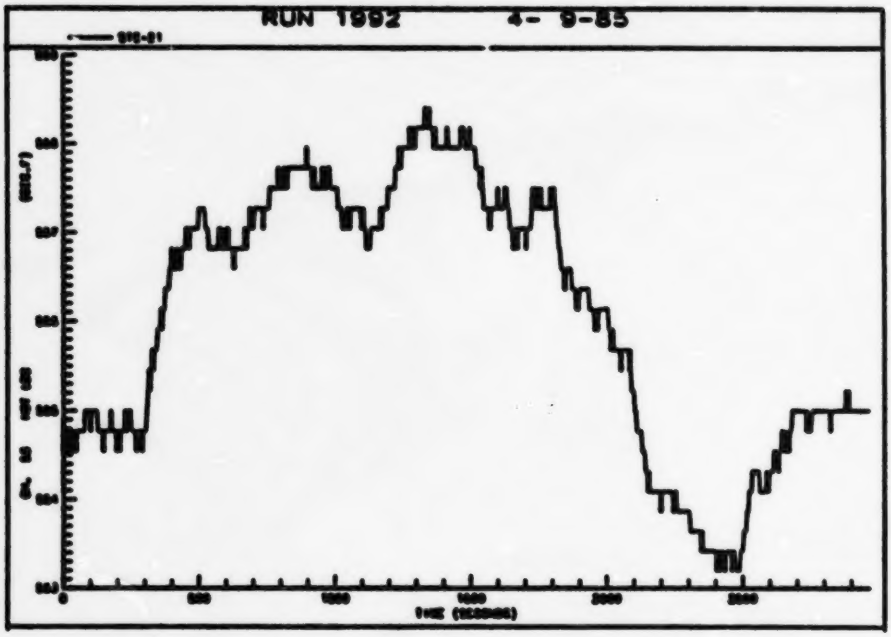

Figure 5-272. Secondary Fluid Temperature (STC-21): Test No. 9 (T-1992)

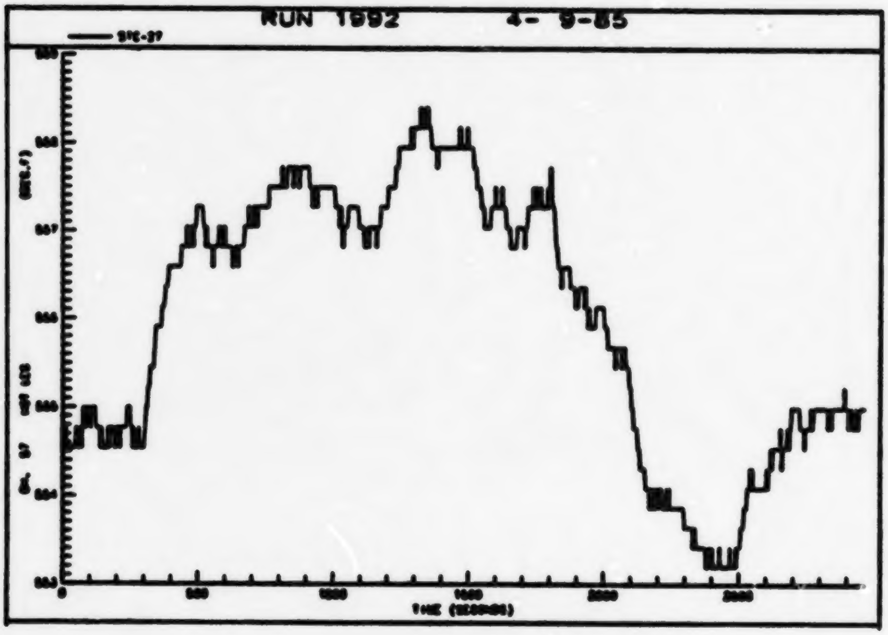

Figure 5-273. Secondary Fluid Temperature (STC-27): Test No. 9 (T-1992)

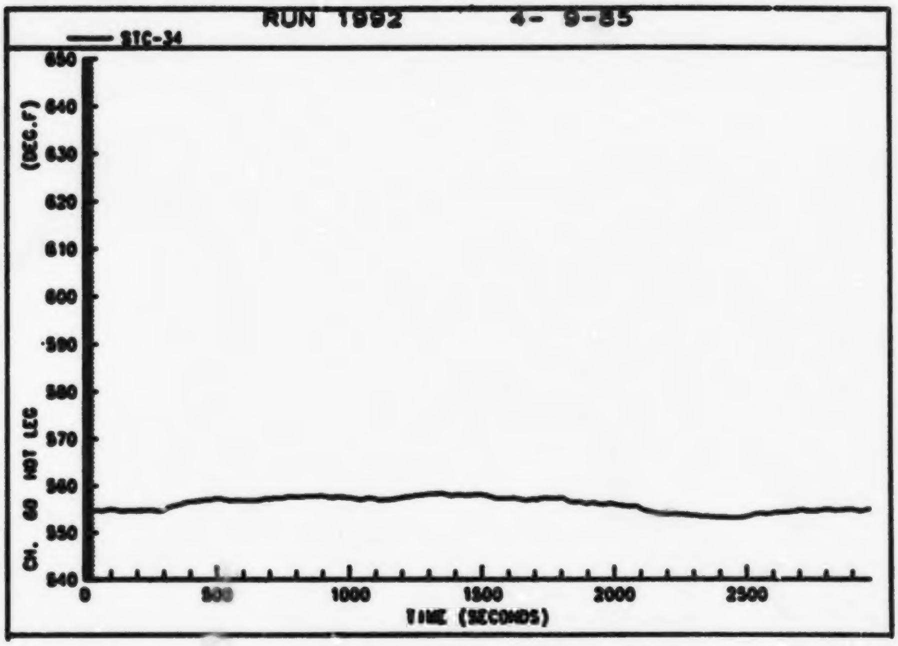

Figure 5-274. Secondary Fluid Temperature (STC-34): Test No. 9 (T-1992)

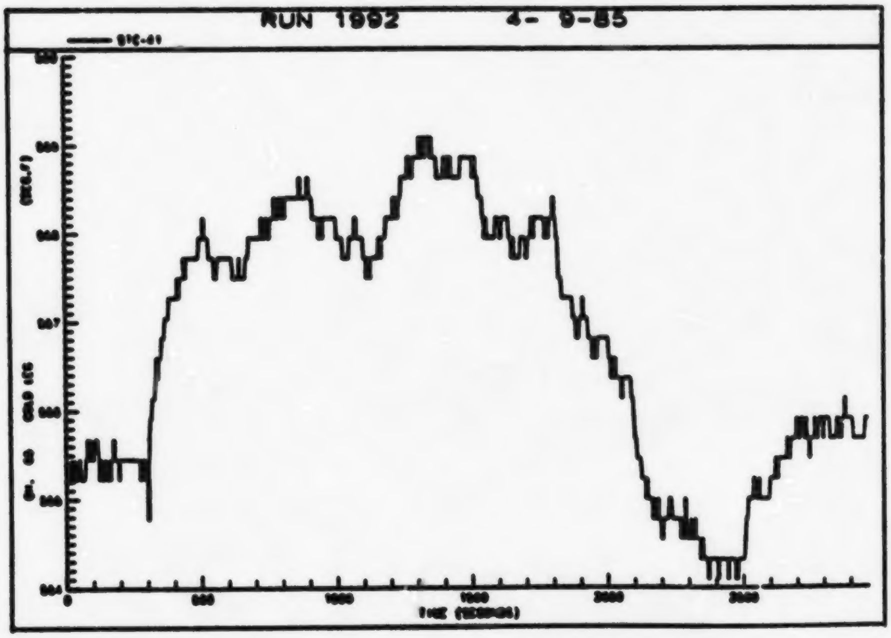

Figure 5-275. Secondary Fluid Temperature (STC-41): Test No. 9 (T-1992)

334

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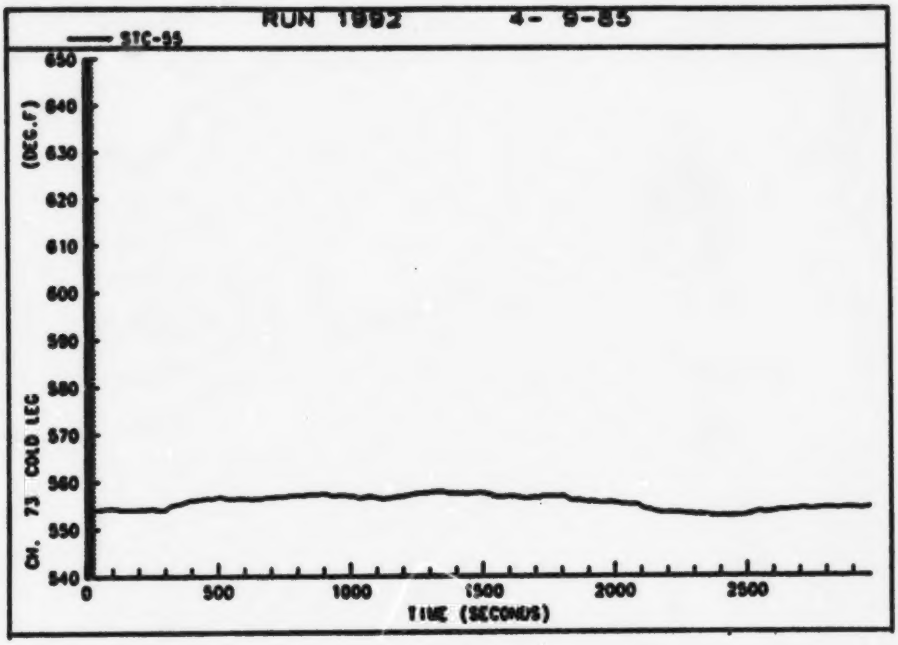

Figure 5-276. Secondary Fluid Temperature (STC-55): Test No. 9 (T-1992)

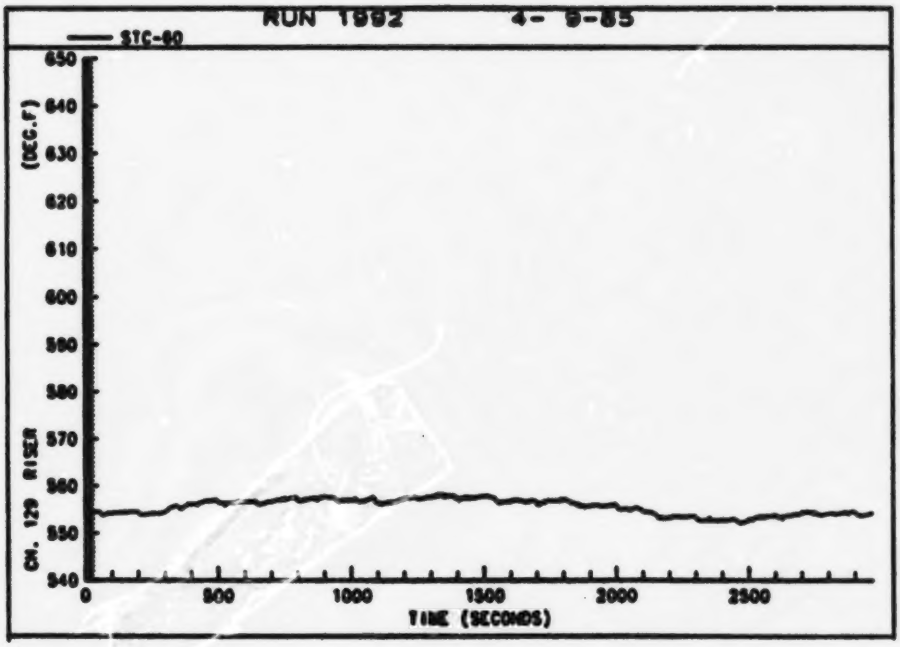

Figure 5-277. Secondary Fluid Temperature (STC-60): Test No. 9 (T-1992)

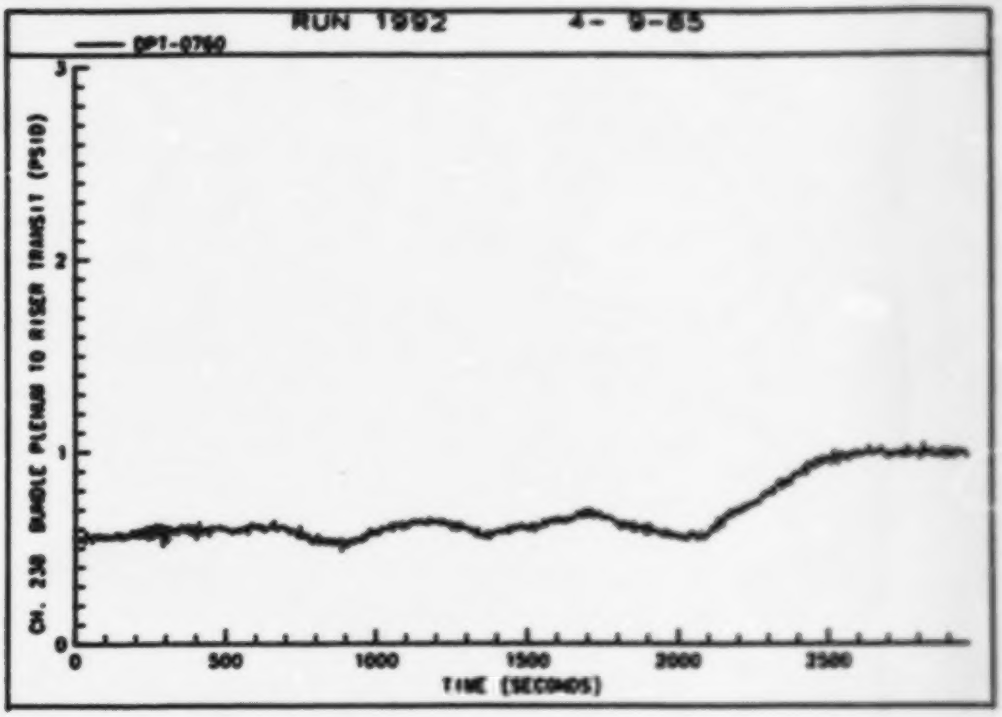

Figure 5-278. Differential Pressure DP-0760: Test No. 9 (T-1992)

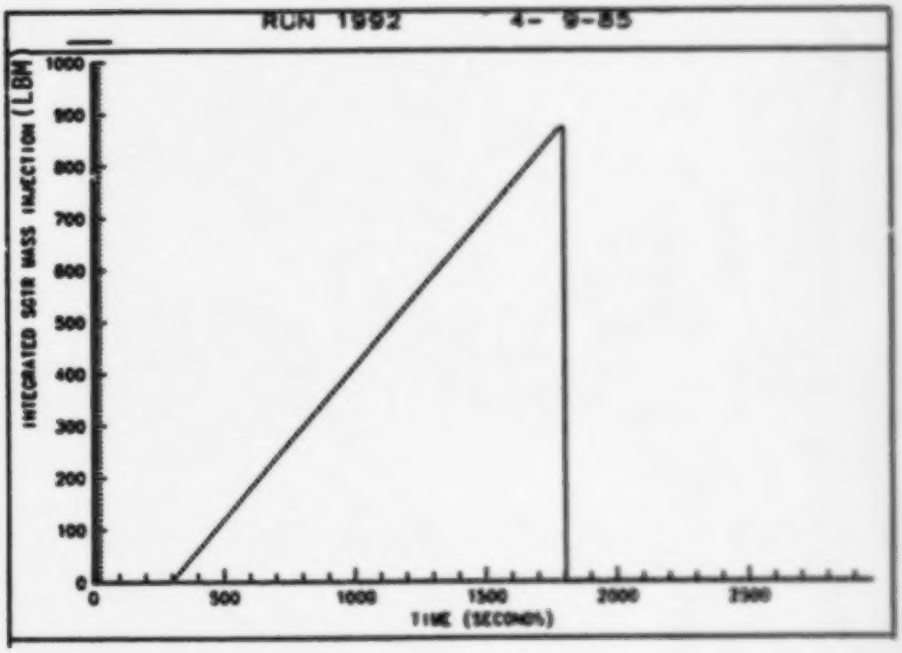

Figure 5-279. Integrated SGTR Flow: Test No. 9 (T-1992)

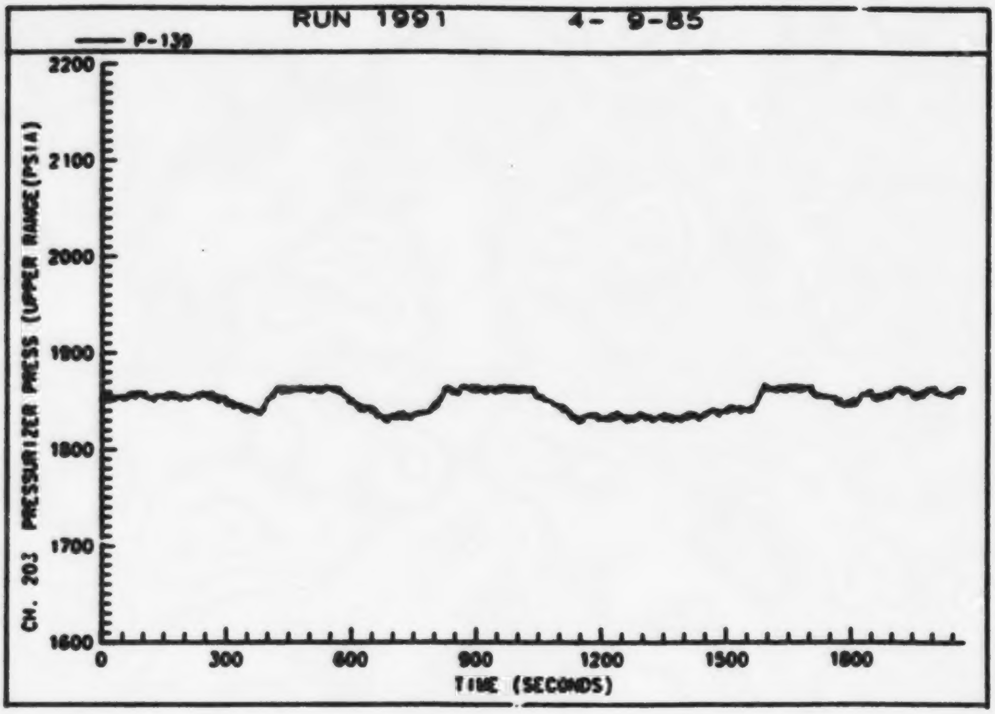

Figure 5-280. Primary System (Pressurizer) Pressure (P-139): Test No. 9 (T-1991)

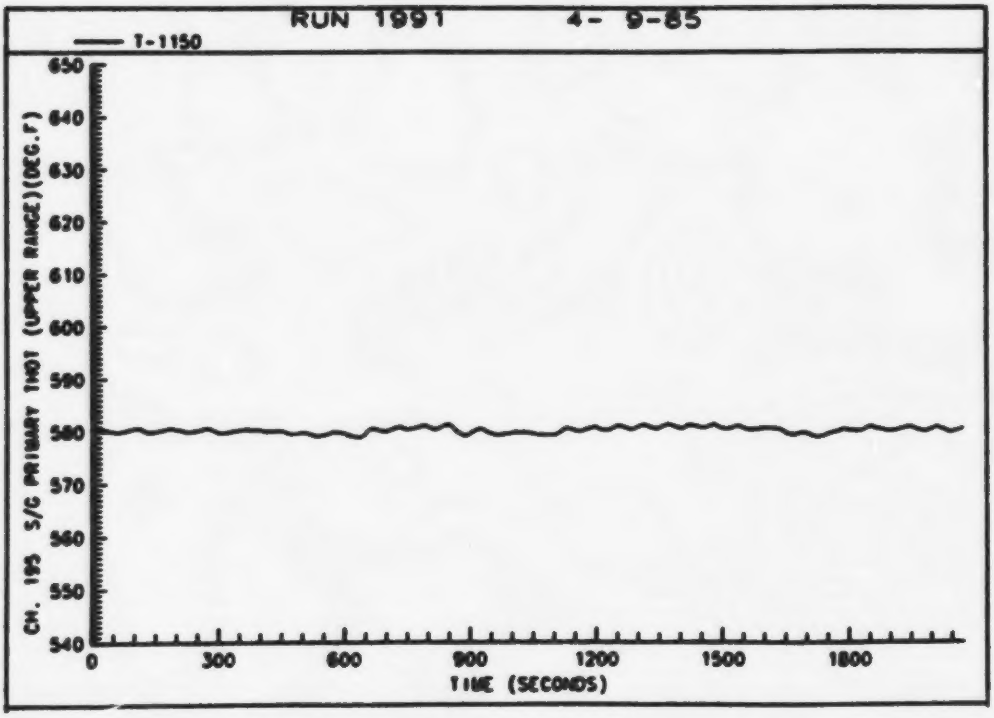

Figure 5-281. Primary Fluid T_{hot} (T-1150): Test No. 9 (T-1991)

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337

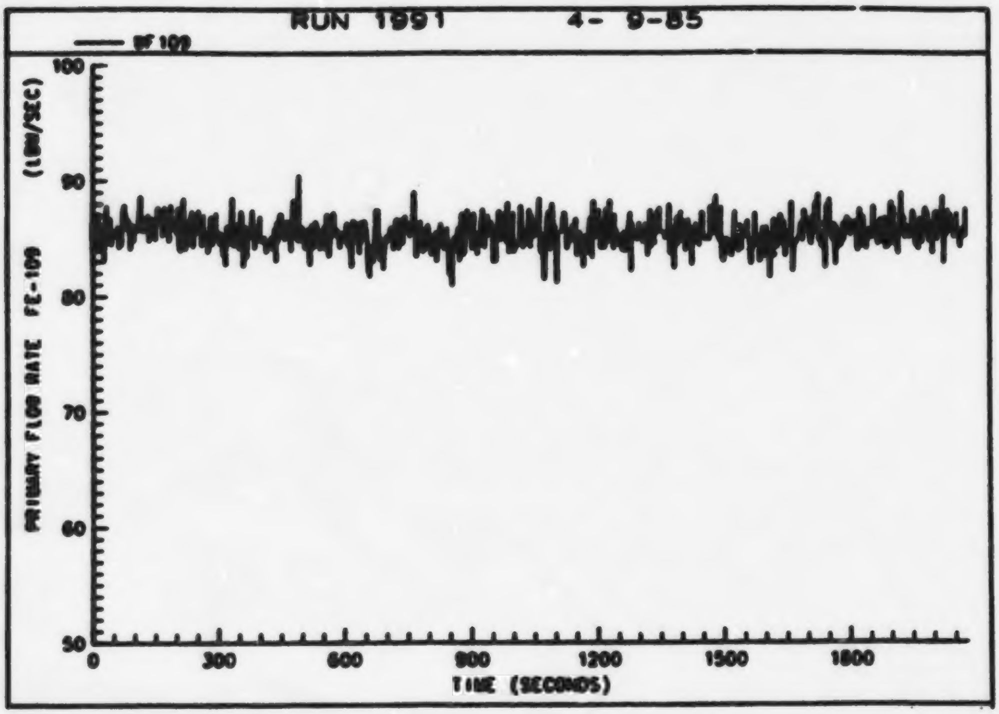

Figure 5-282. Primary Fluid Flow Rate (WF-109): Test No. 9 (T-1991)

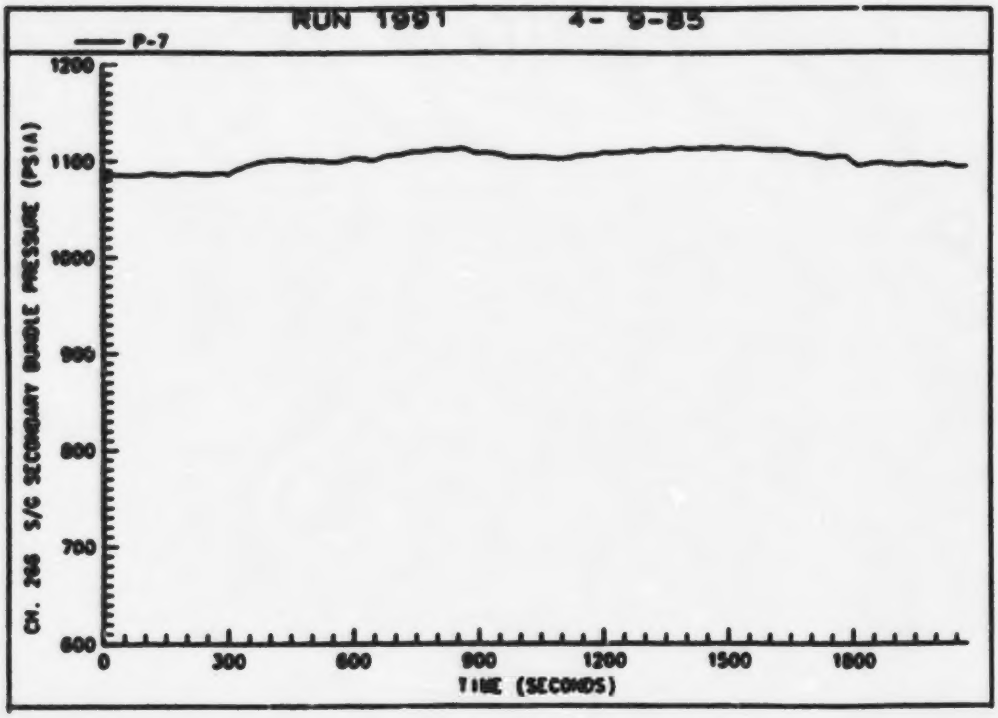

Figure 5-283. Secondary Side Pressure (P-7): Test No. 9 (T-1991)

338

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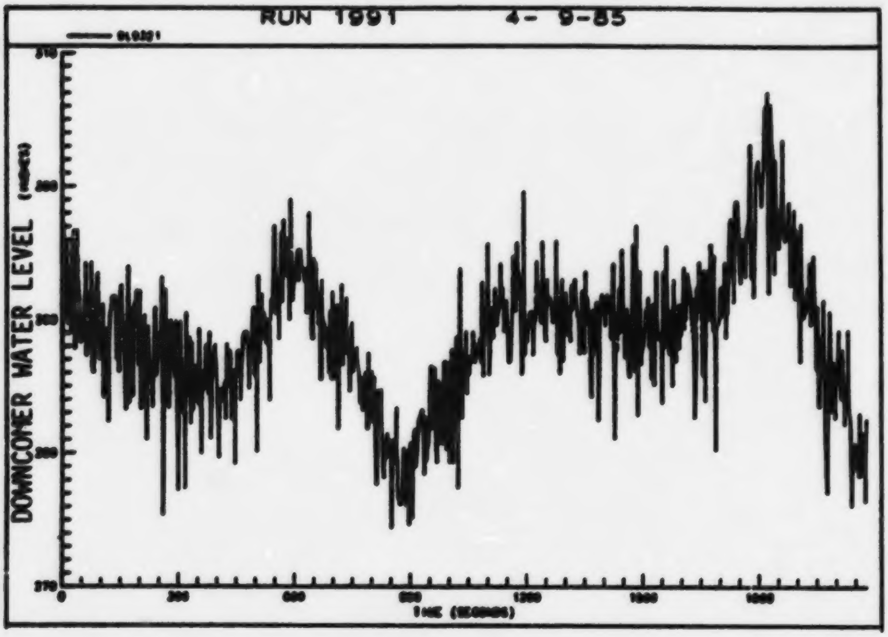

Figure 5-284. Downcomer Water Level - Wide Range (WL-9321): Test No. 9 (T-1991)

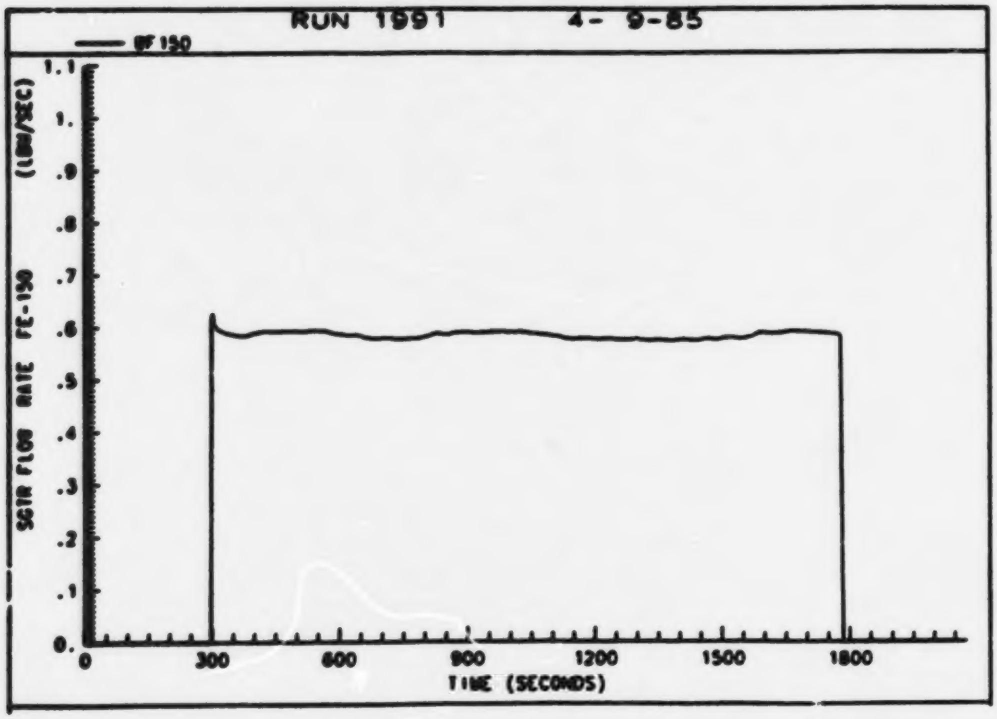

Figure 5-285. SGTR Flow Rate (WF-150): Test No. 9 (T-1991)

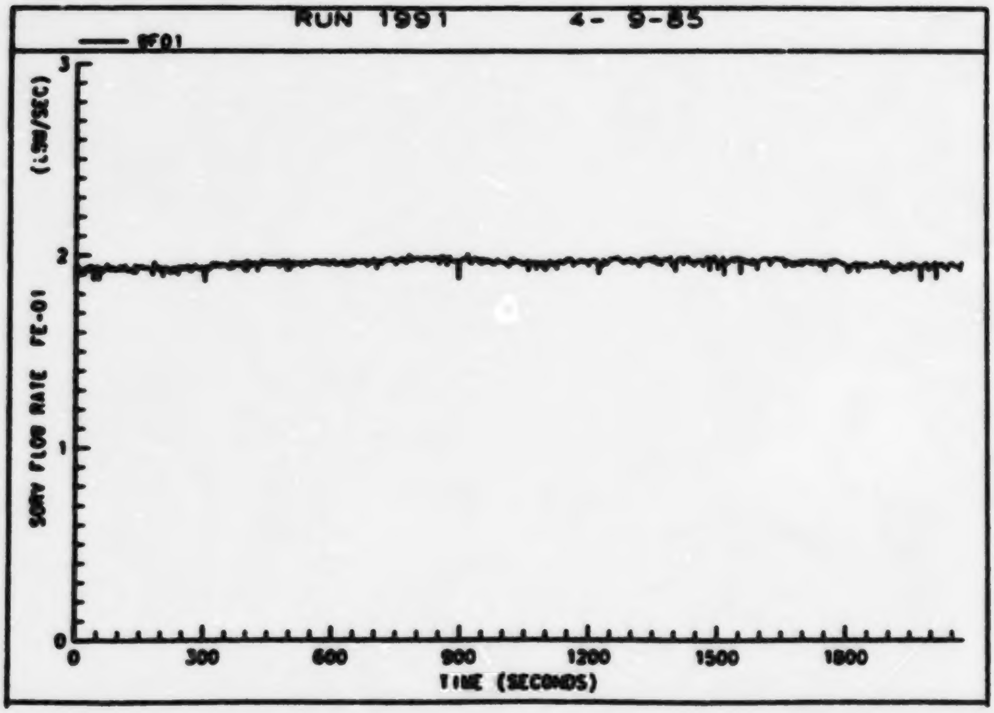

Figure 5-286. SORV Flow Rate (WF-01): Test No. 9 (T-1991)

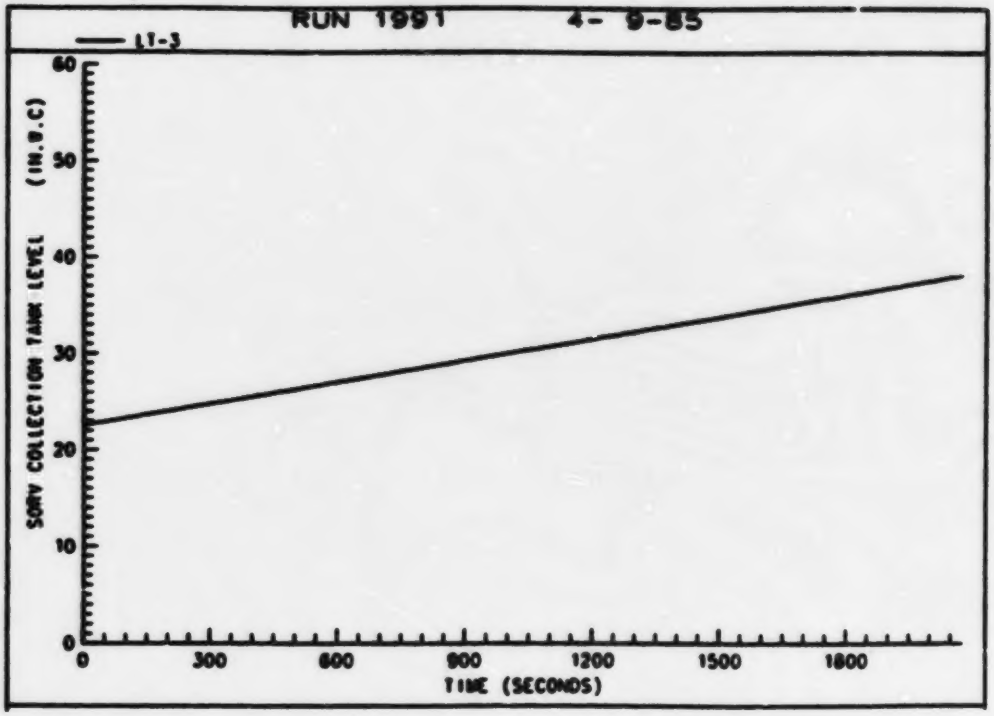

Figure 5-287. SORV Tank Level (LT-3): Test No. 9 (T-1991)

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340

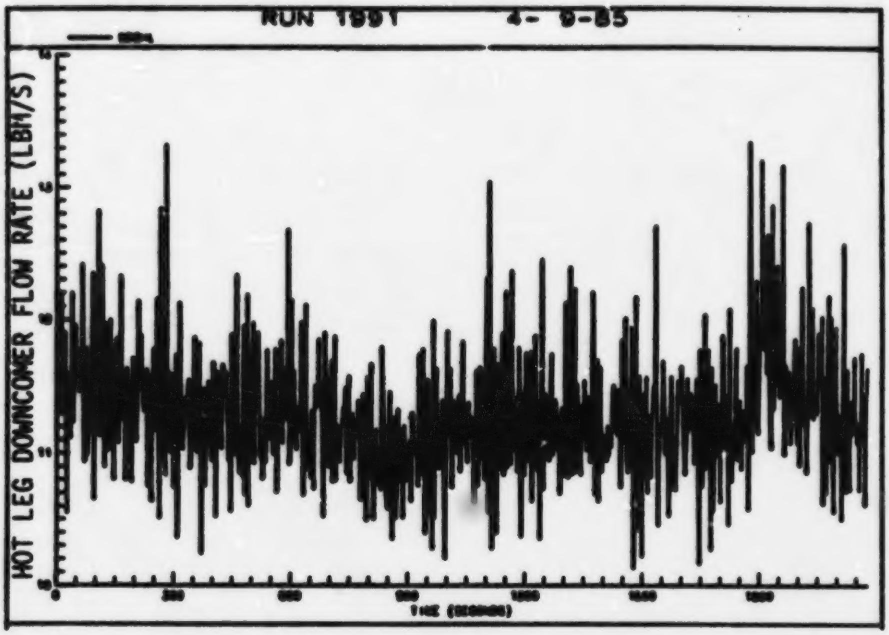

Figure 5-288. Hot Leg Downcomer Flow Rate (WDHCL): Test No. 9 (T-1991)

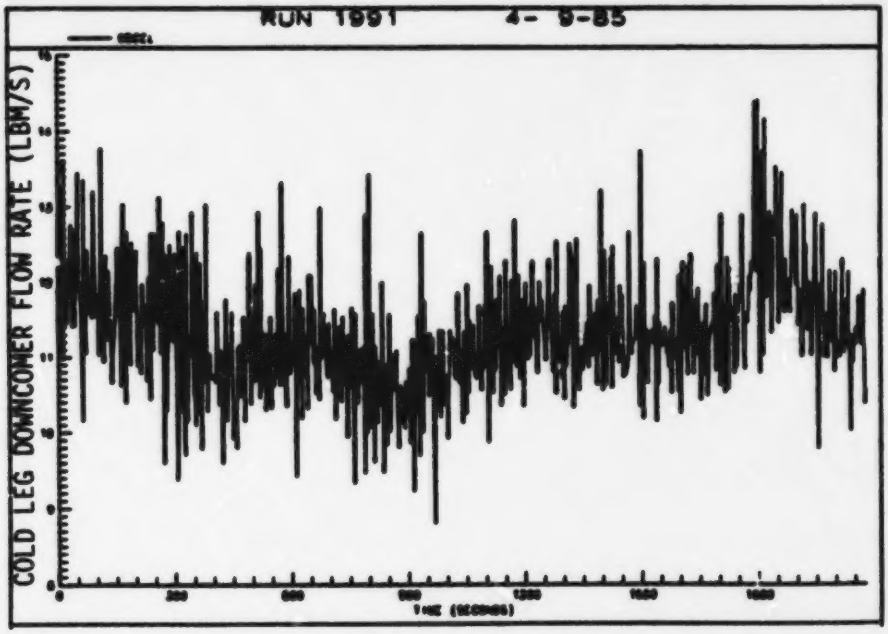

Figure 5-289. Cold Leg Downcomer Flow Rate (WDCCL): Test No. 9 (T-1991)

341

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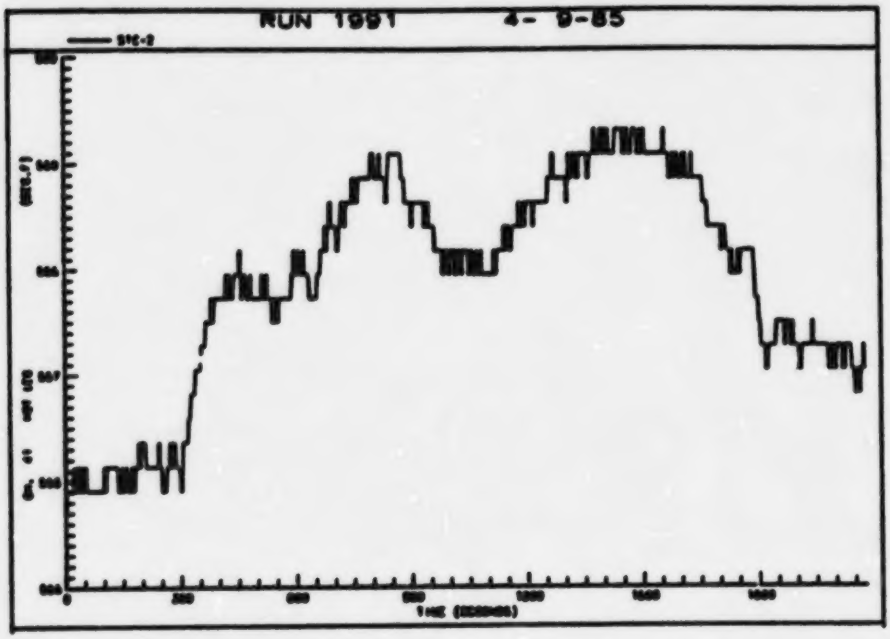

Figure 5-290. Secondary Fluid Temperature (STC-2): Test No. 9 (T-1991)

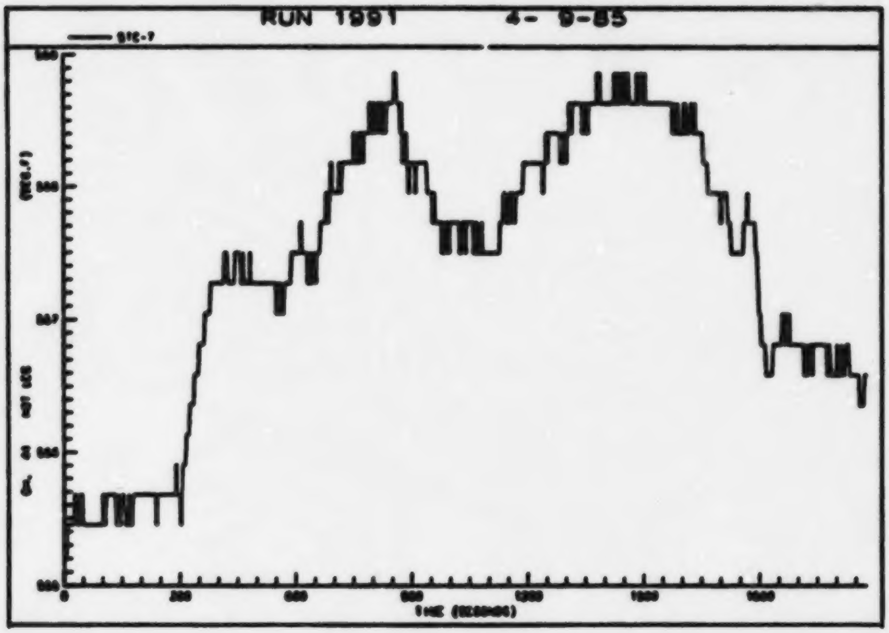

Figure 5-291. Secondary Fluid Temperature (STC-7): Test No. 9 (T-1991)

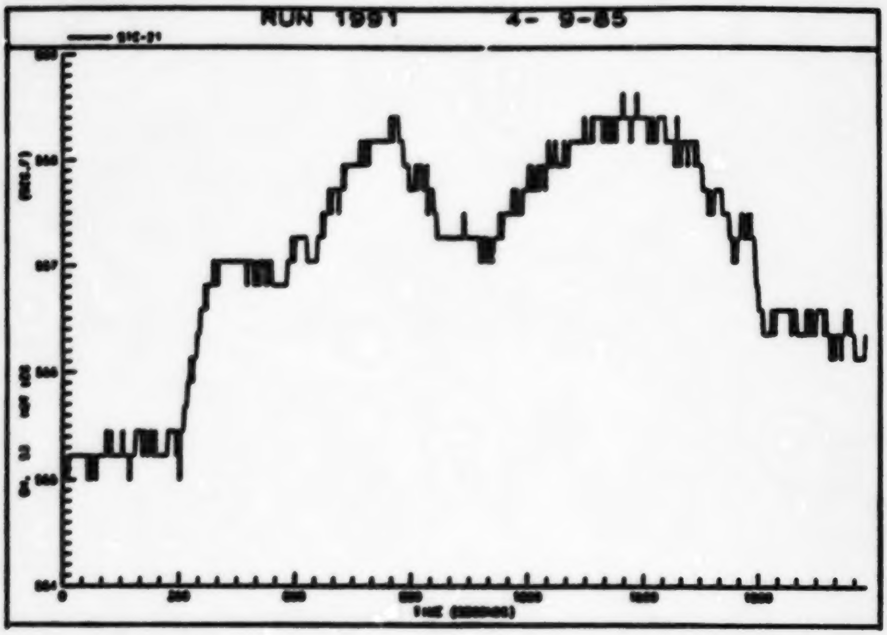

Figure 5-292. Secondary Fluid Temperature (STC-21): Test No. 9 (T-1991)

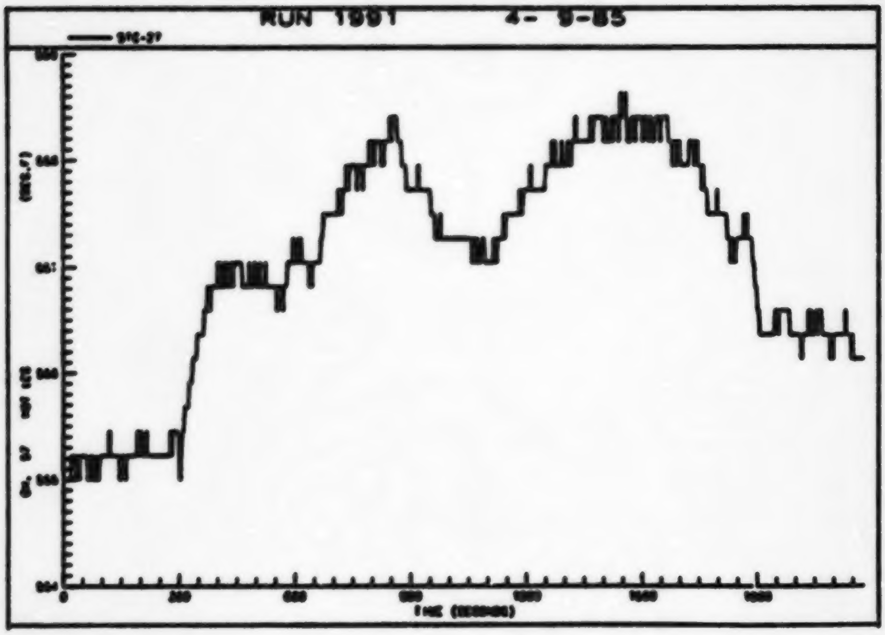

Figure 5-293. Secondary Fluid Temperature (STC-27): Test No. 9 (T-1991)

343

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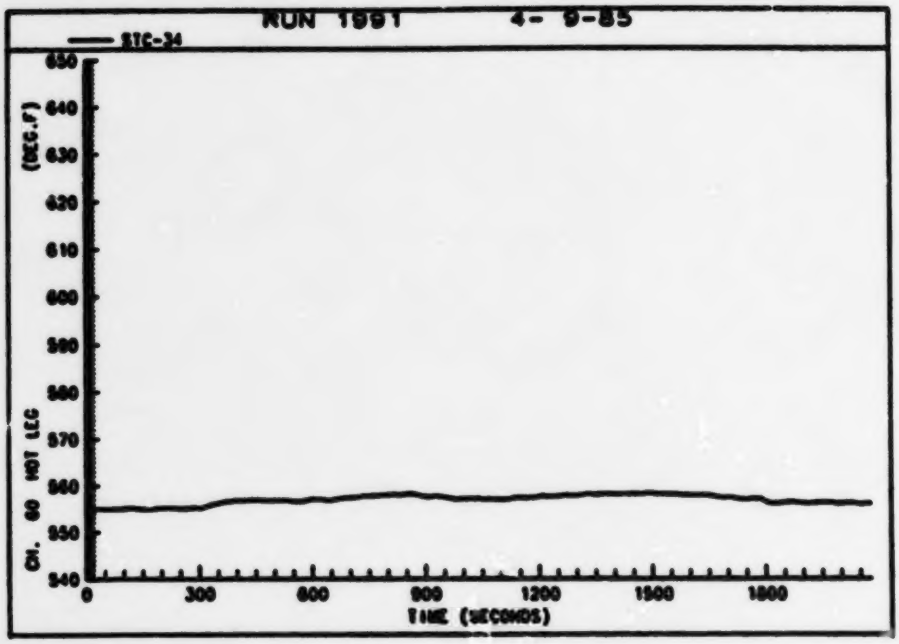

Figure 5-294. Secondary Fluid Temperature (STC-34): Test No. 9 (T-1991)

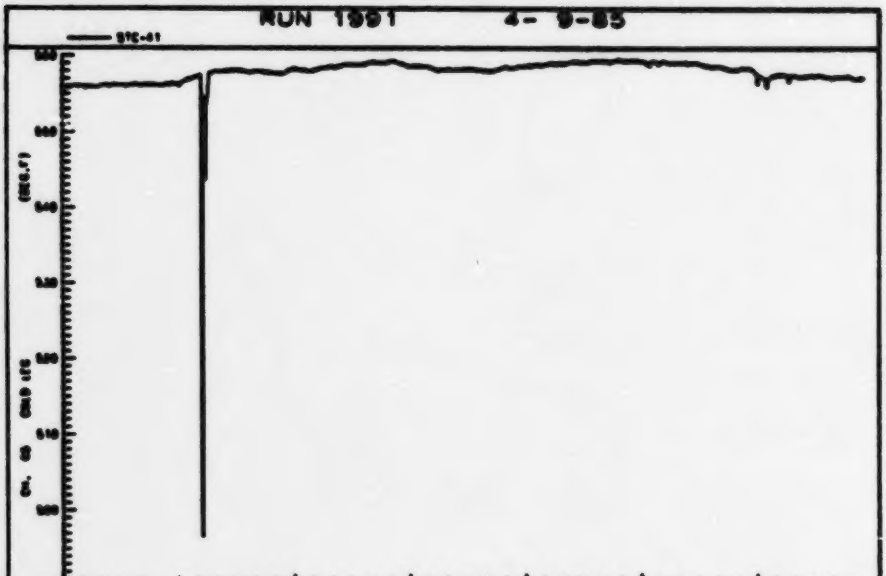

Figure 5-295. Secondary Fluid Temperature (STC-41): Test No. 9 (T-1991)

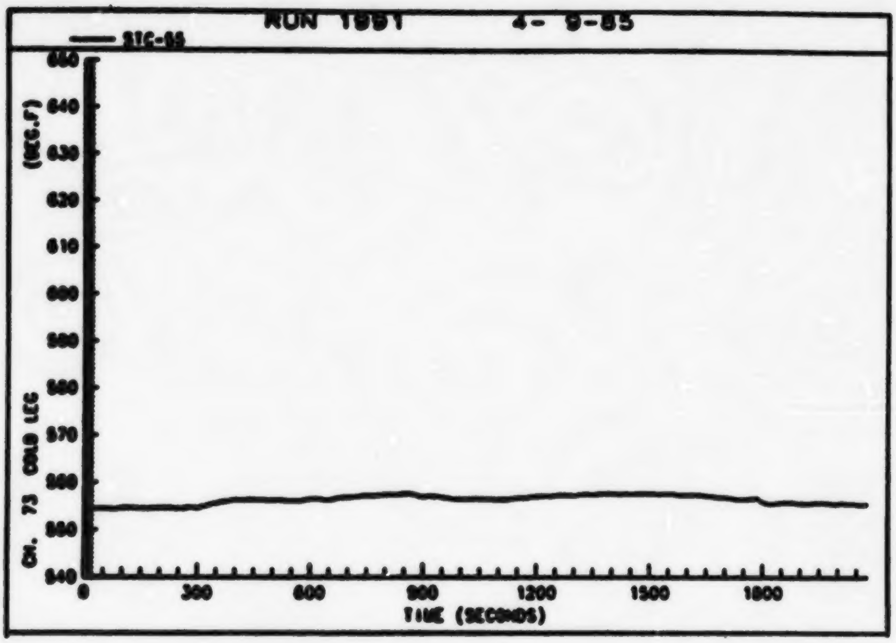

Figure 5-296. Secondary Fluid Temperature (STC-55): Test No. 9 (T-1991)

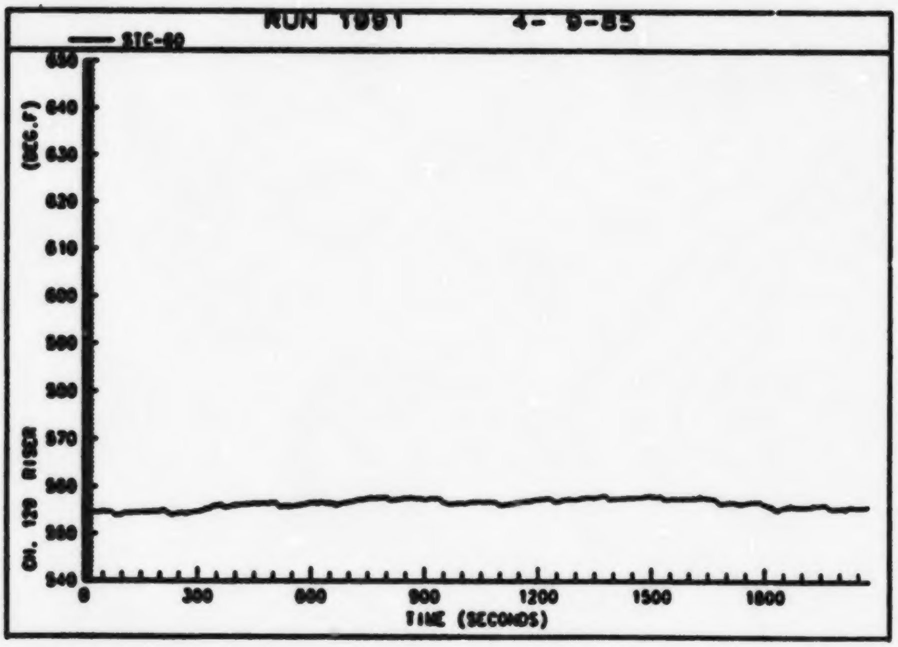

Figure 5-297. Secondary Fluid Temperature (STC-60): Test No. 9 (T-1991)

345

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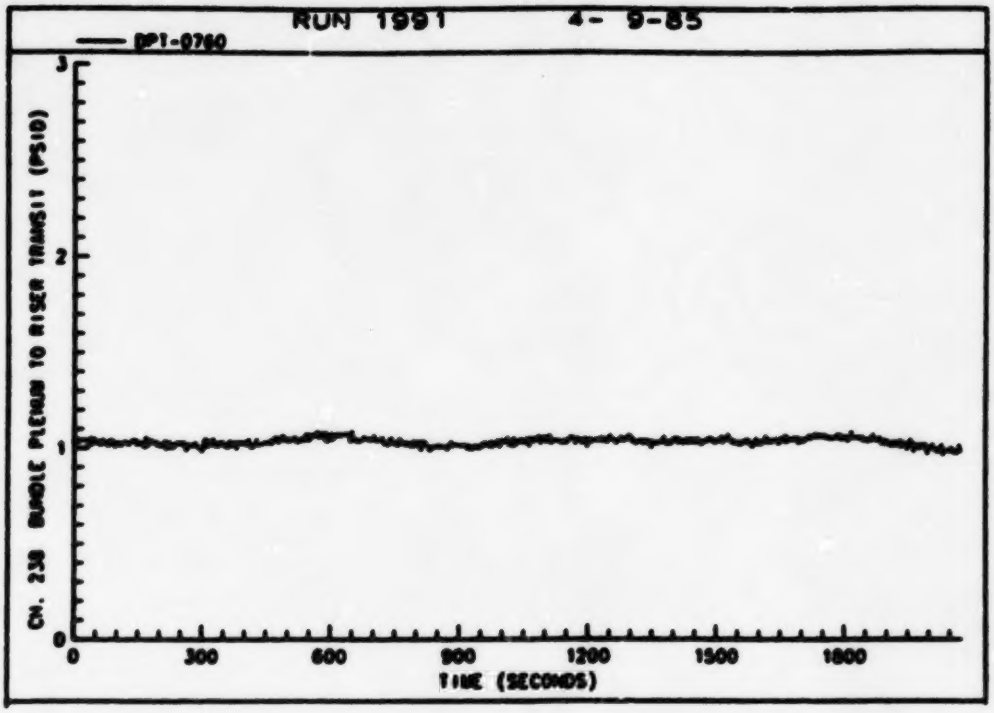

Figure 5-298. Differential Pressure DP-0760: Test No. 9 (T-1991)

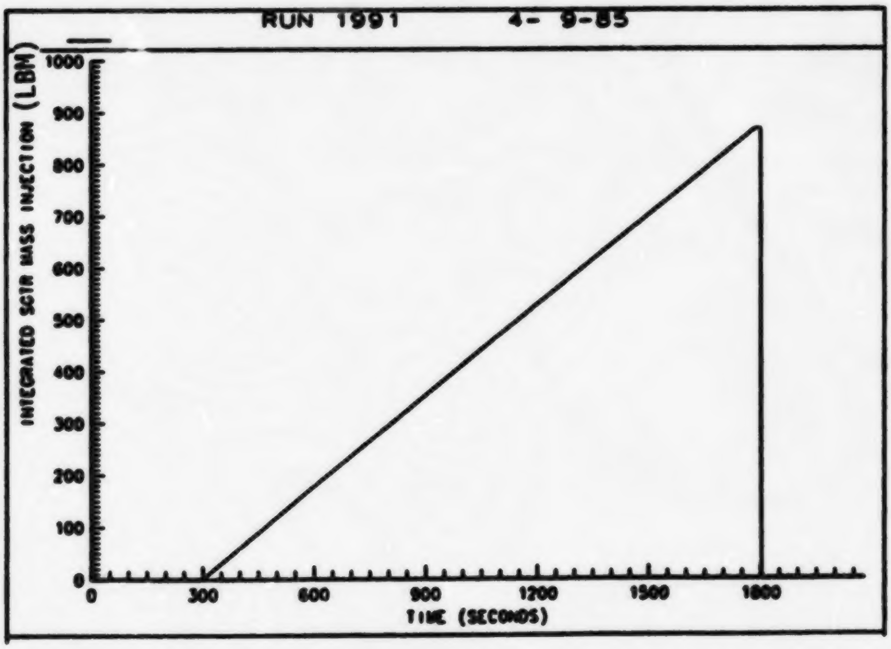

Figure 5-299. Integrated SGTR Flow: Test No. 9 (T-1991)

346

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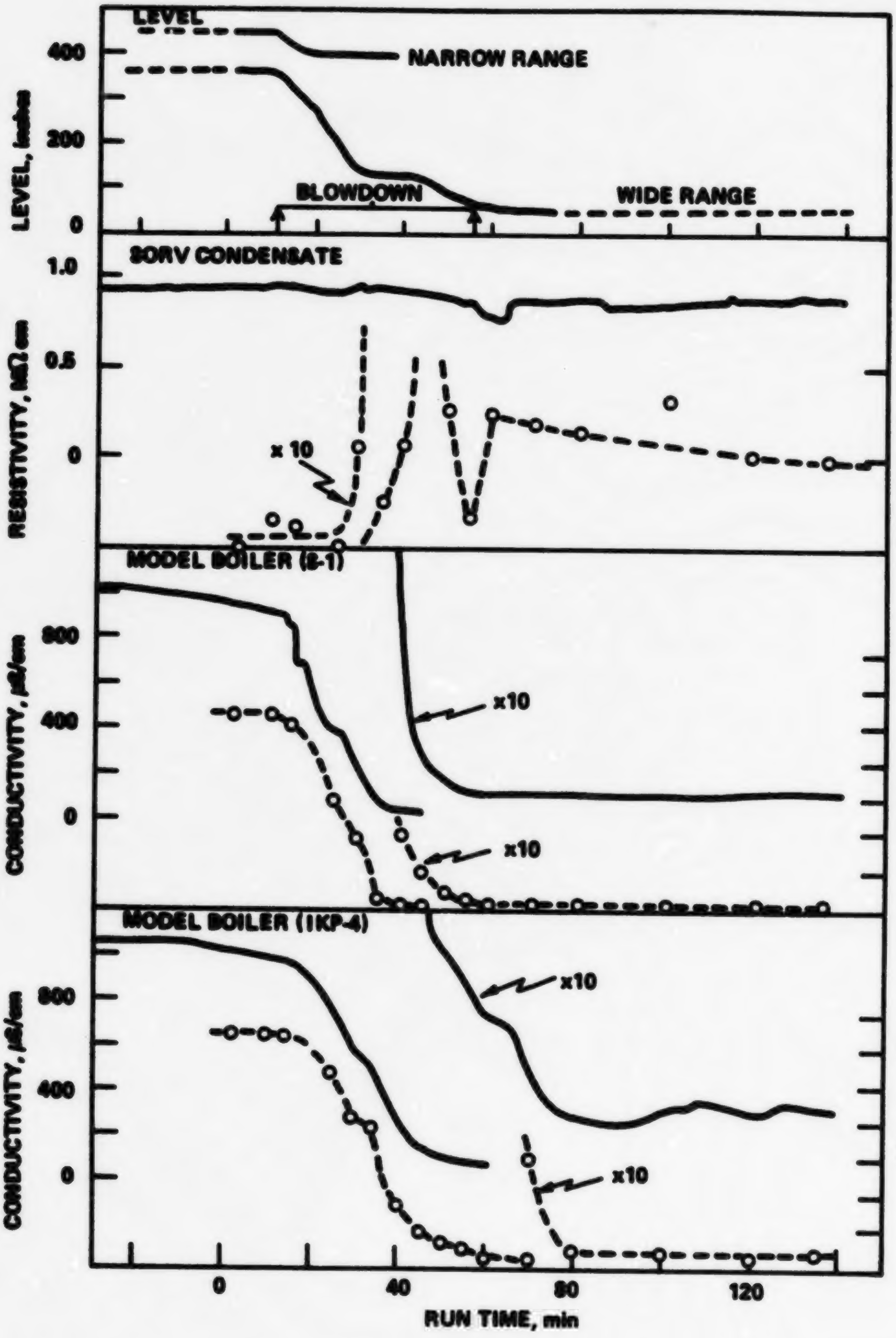

Figure 5-300. Variation in Tracer Concentrations: Blowdown Phase, Test No. 9 (T-1988)

——— LEVEL, RESISTIVITY OR CONDUCTIVITY

—o— LITHIUM CONCENTRATION

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347

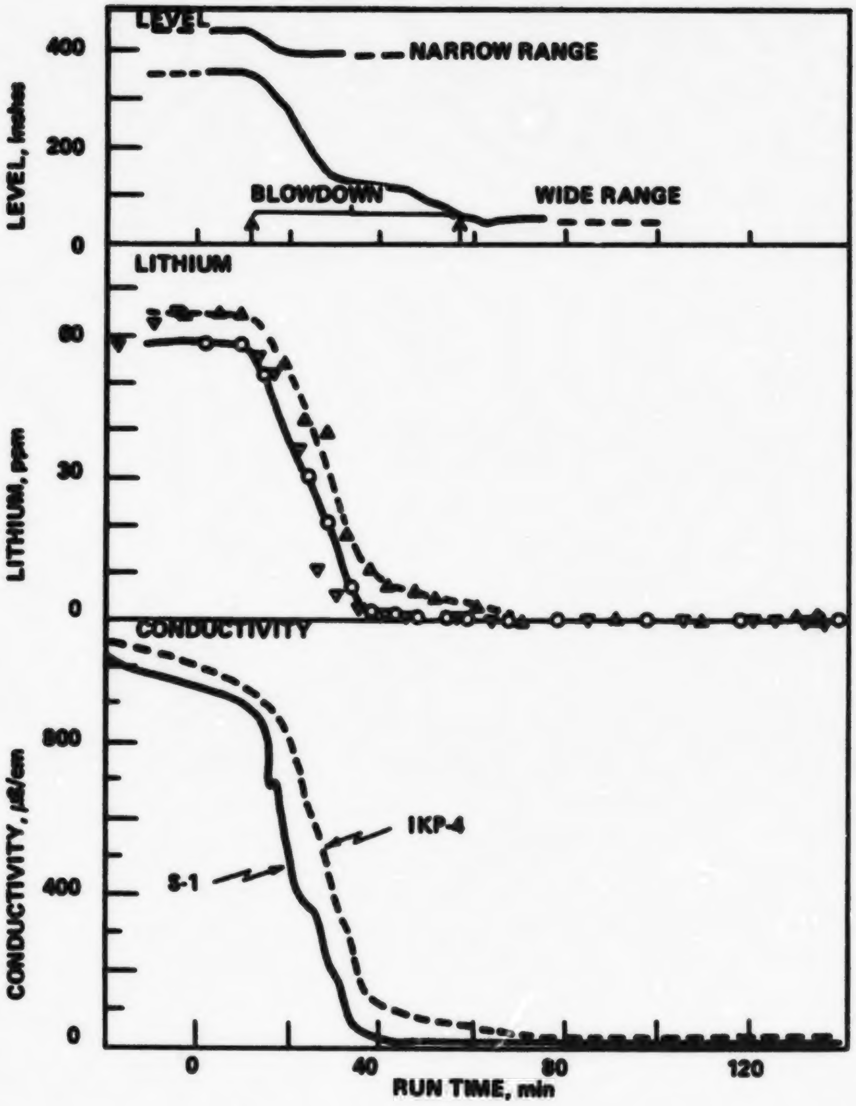

Figure 5-301. Comparison Between S-1 (○), IKP-4 (▲) and Blowdown (▽) Results After Correcting for Sample Line Delays: Blowdown Phase, Test No. 9 (T-1988)

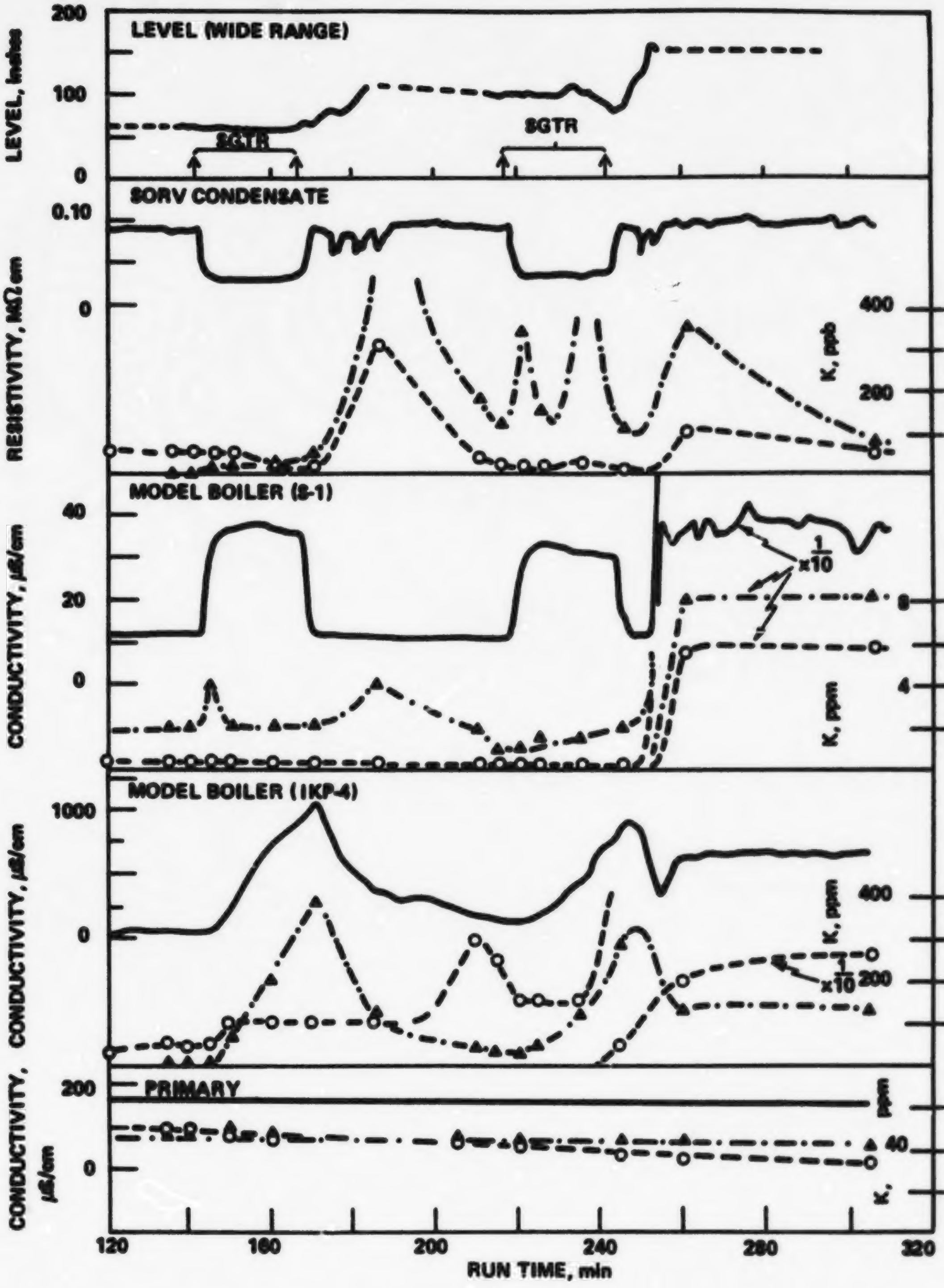

Figure 5-302. Variation in Tracer Concentrations: SGTRs at 64 and 102 in., Test No. 9 (T-1989 and T-1990)

— ·▲— · POTASSIUM CONCENTRATION

——— LEVEL, RESISTIVITY OR CONDUCTIVITY

— ○ — LITHIUM CONCENTRATION

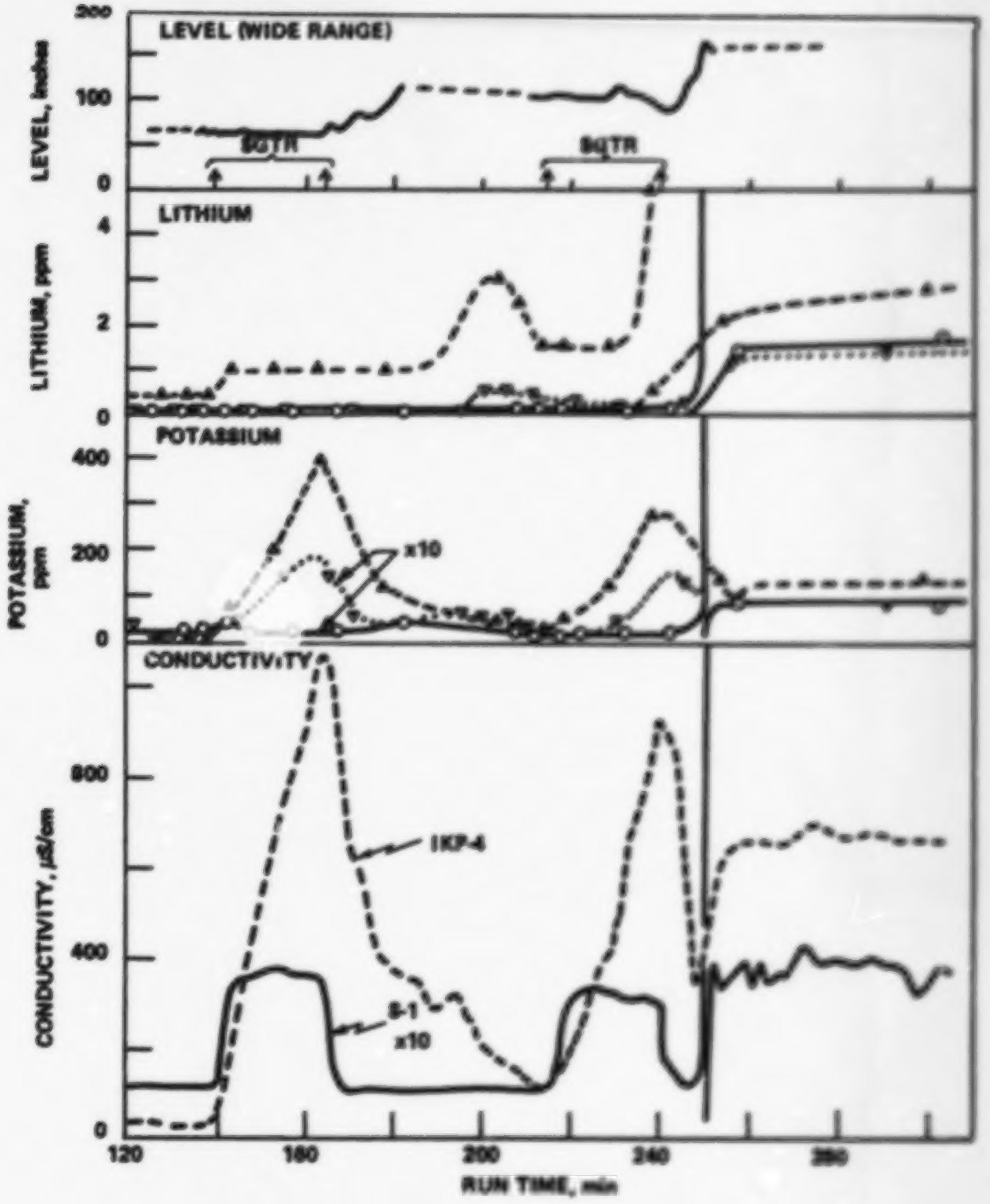

Figure 5-303. Comparison Between S-1 (○), IKP-4 (▲) and Blowdown (▽) Results After Correcting for Sample Time Delays: SGTRs at 64 and 102 in., Test No. 9 (T-1989 and T-1990)

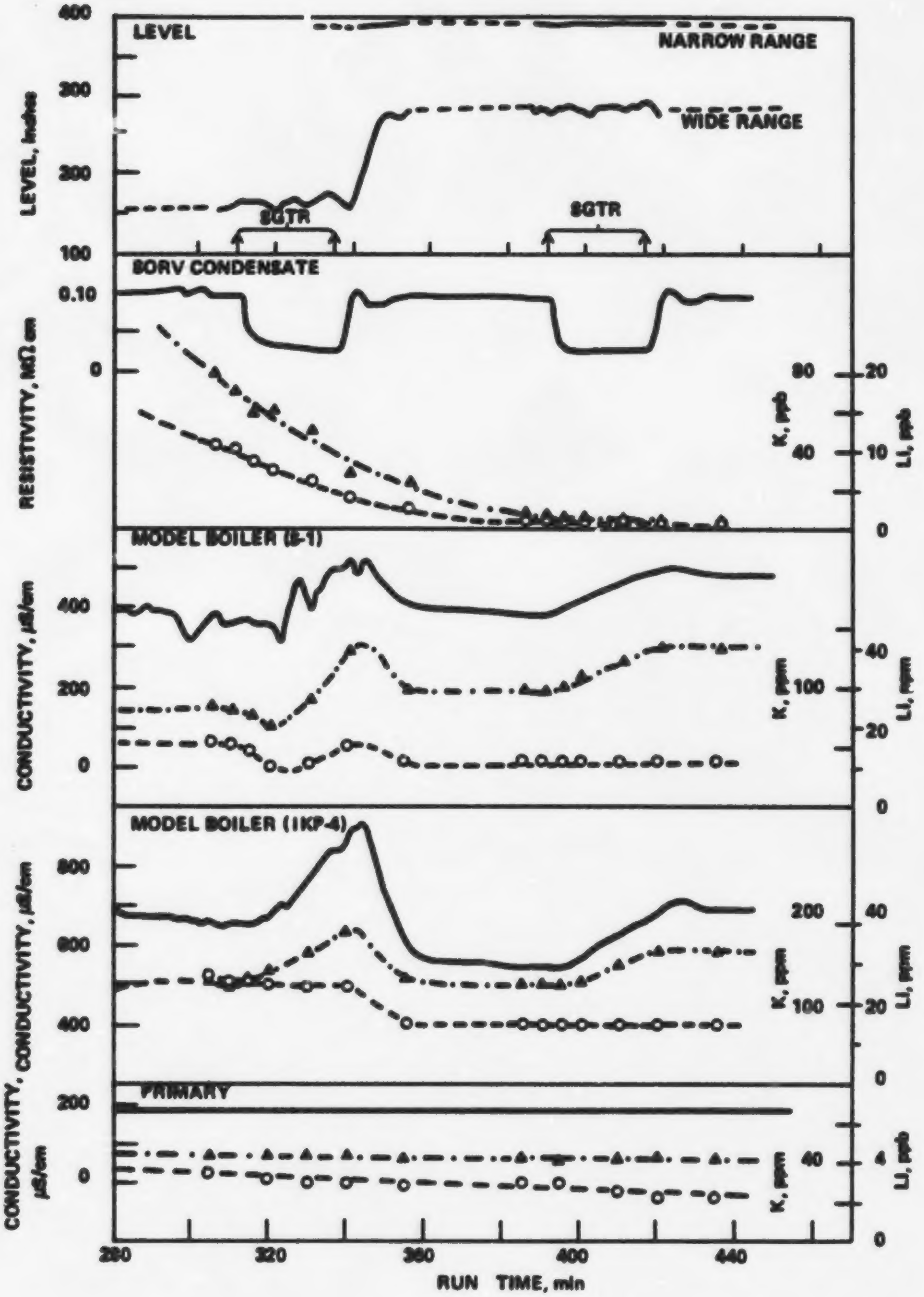

Figure 5-304. Variation in Tracer Concentrations: SGTRs at 165 and 285 in., Test No. 9 (T-1991 and T-1992)

—·▲—· POTASSIUM CONCENTRATION

——— LEVEL, RESISTIVITY OR CONDUCTIVITY

— ○ — LITHIUM CONCENTRATION

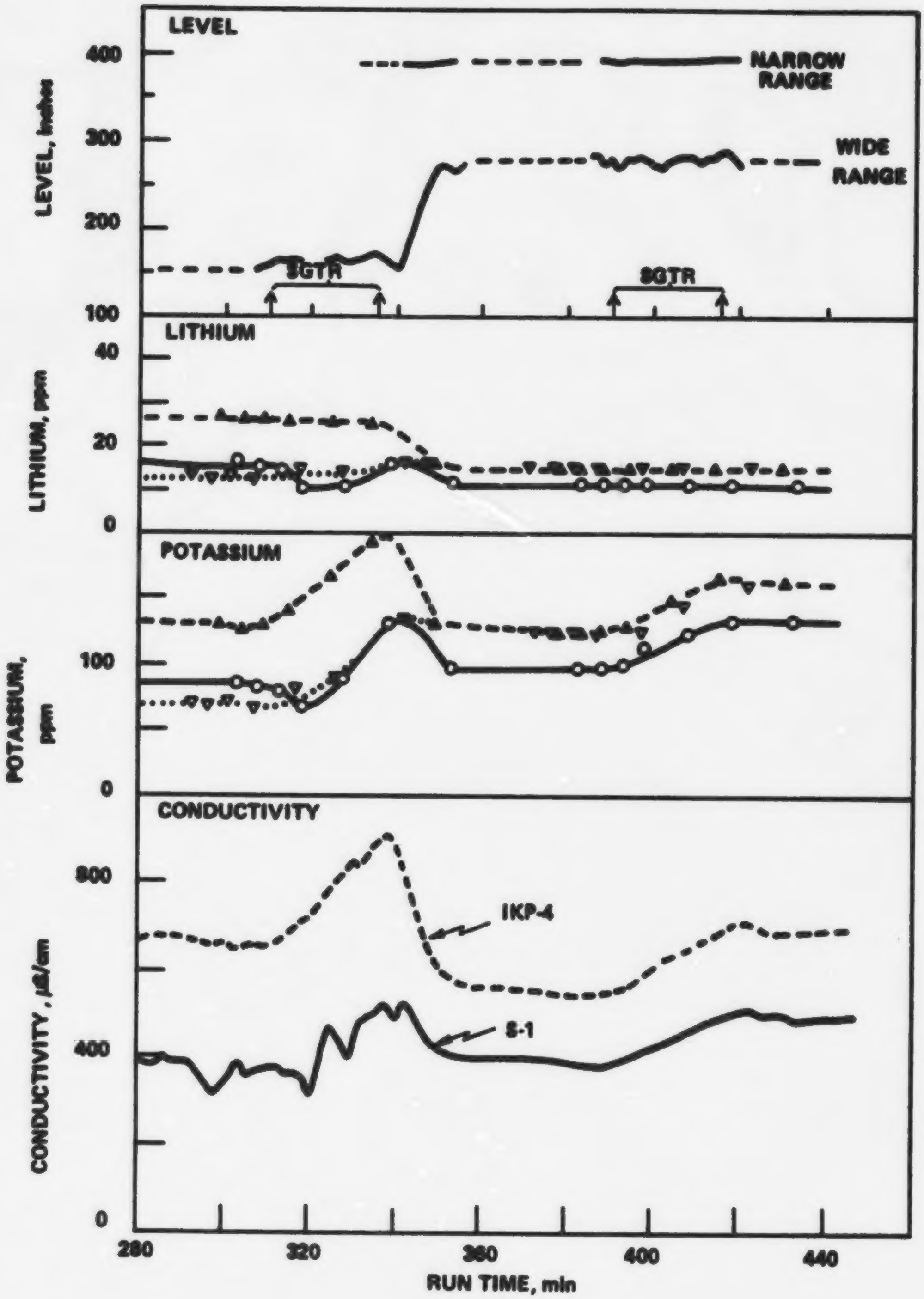

Figure 5-305. Comparison Between S-1 (○), IKP-4 (▲) and Blowdown (▽) Results After Correcting for Sample Line Delays: SGTRs at 165 and 285 in., Test No. 9 (T-1991 and T-1992)

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352

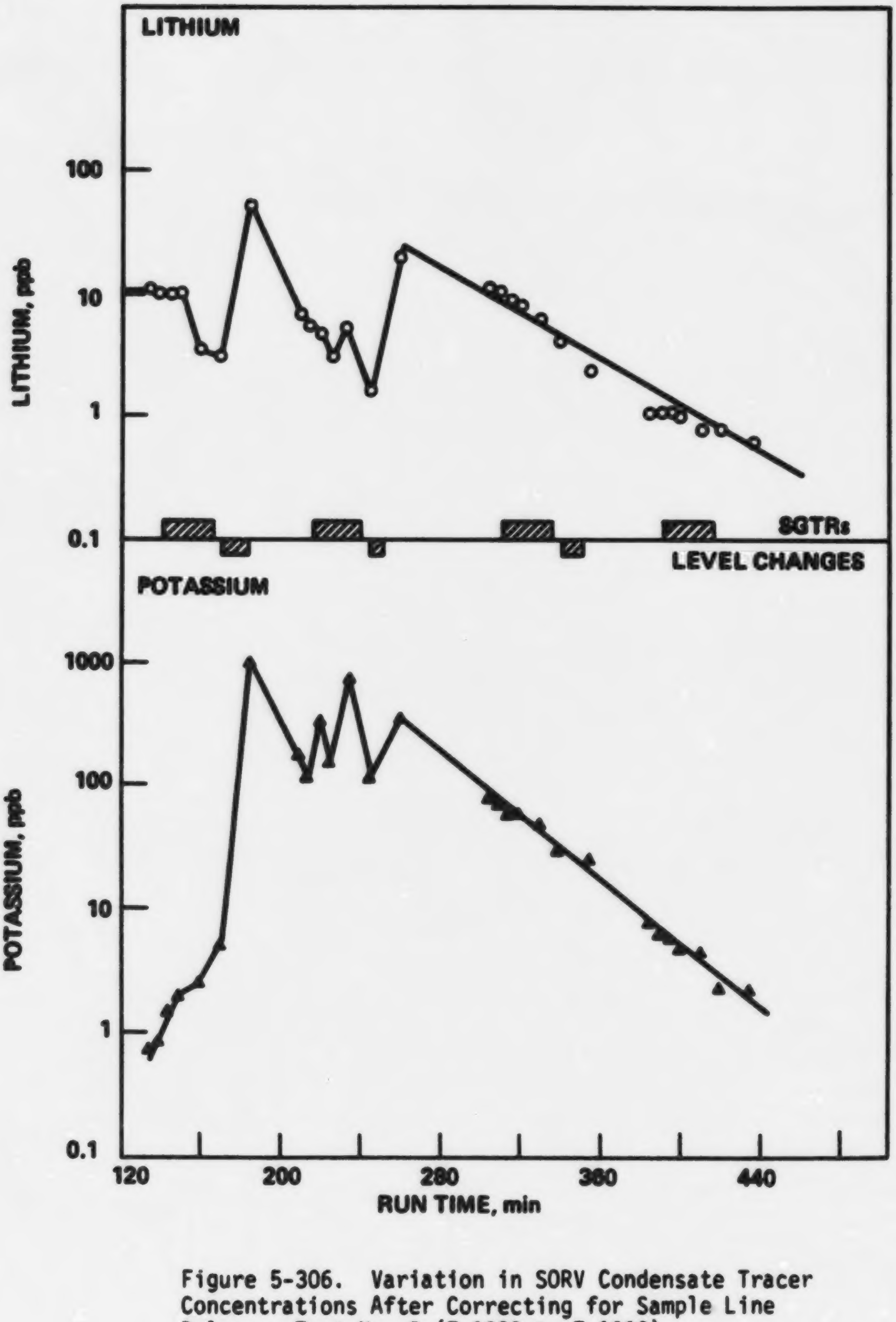

Figure 5-306. Variation in SORV Condensate Tracer Concentrations After Correcting for Sample Line Delays: Test No. 9 (T-1988 to T-1992)

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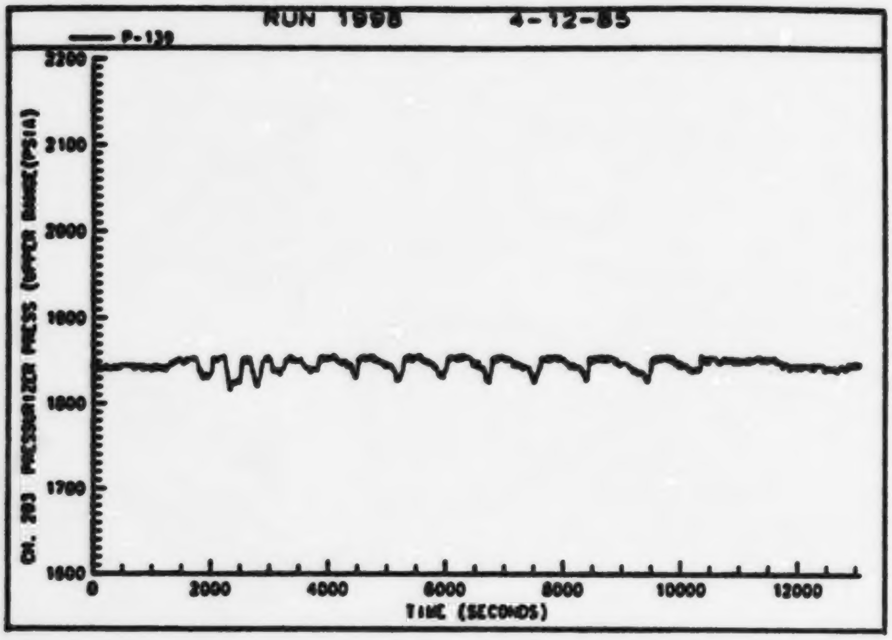

Figure 5-307. Primary System (Pressurizer) Pressure (P-139): Test No. 10 (T-1998)

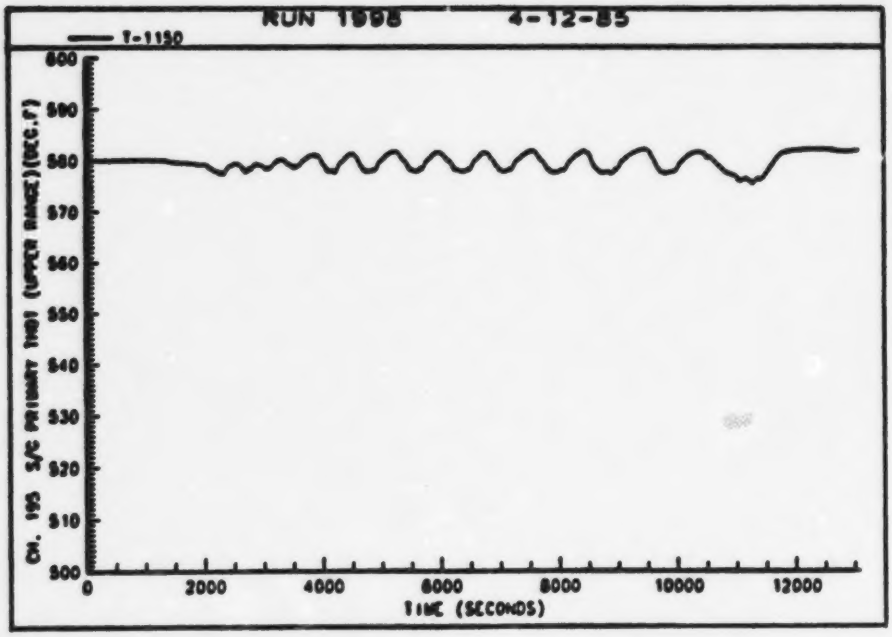

Figure 5-308. Primary Fluid T_{hot} (T-1150): Test No. 10 (T-1998)

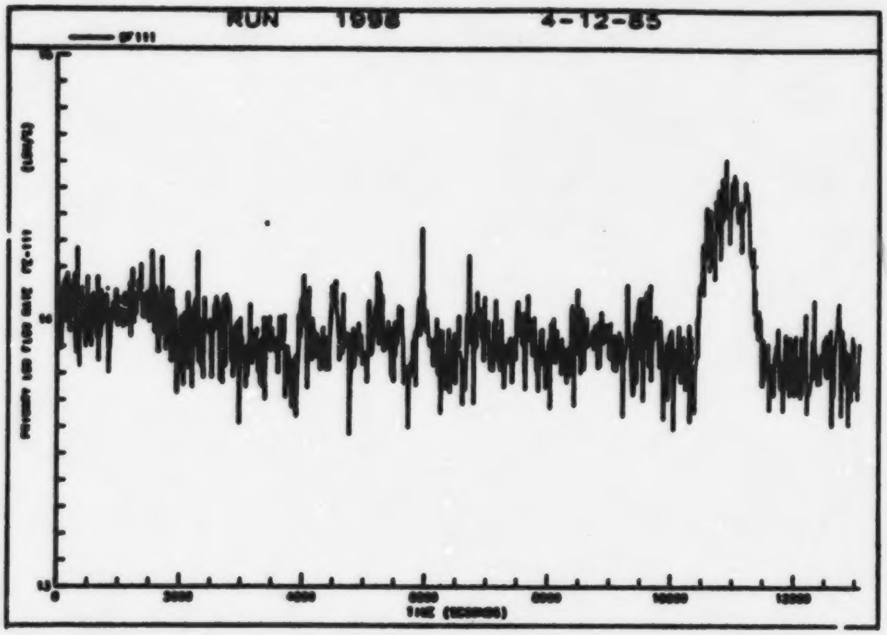

Figure 5-309. Primary Fluid Flow Rate (WF-111):
Test No. 10 (T-1998)

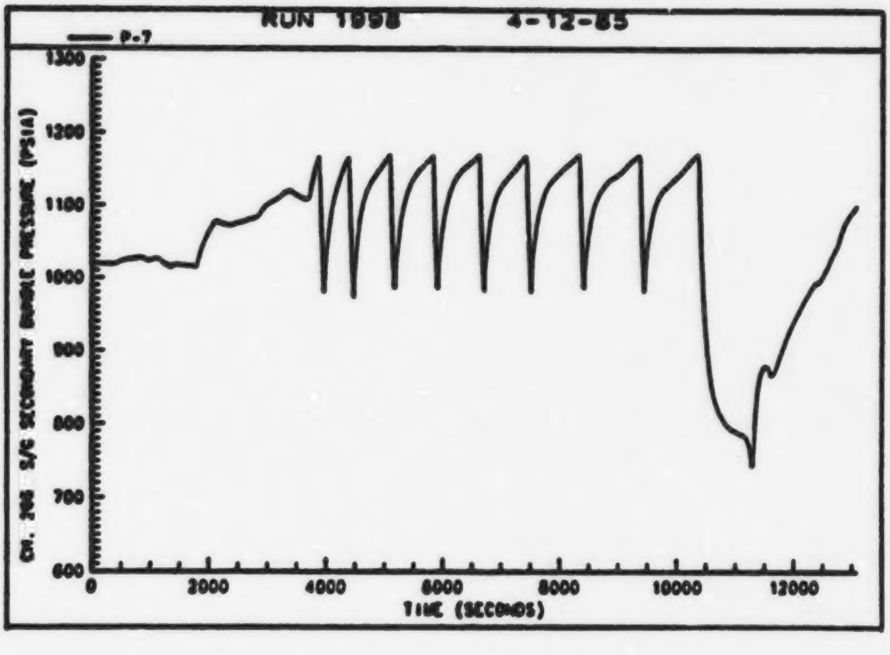

Figure 5-310. Secondary Side Pressure (P-7):
Test No. 10 (T-1998)

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355

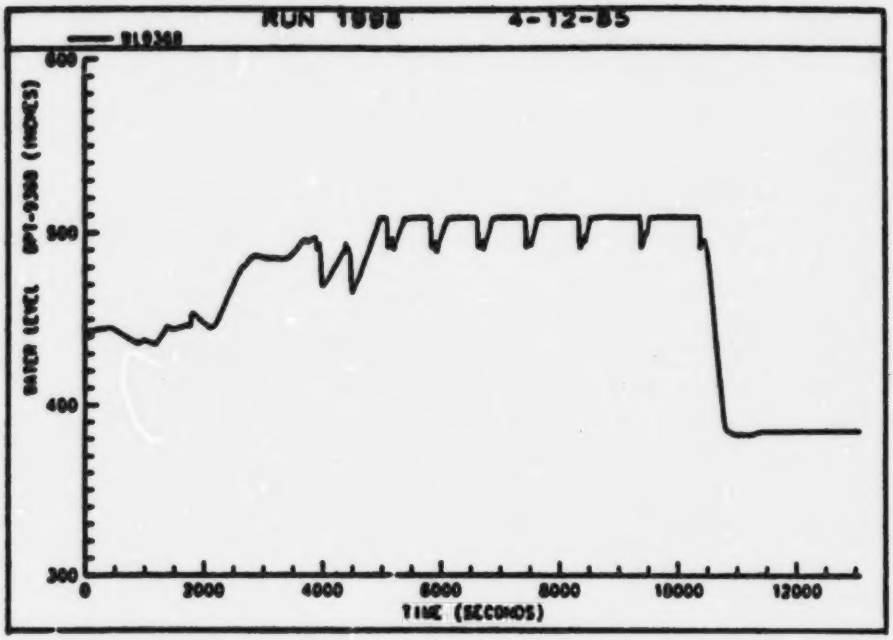

Figure 5-311. Downcomer Water Level - Narrow Range (WL-9368): Test No. 10 (T-1998)

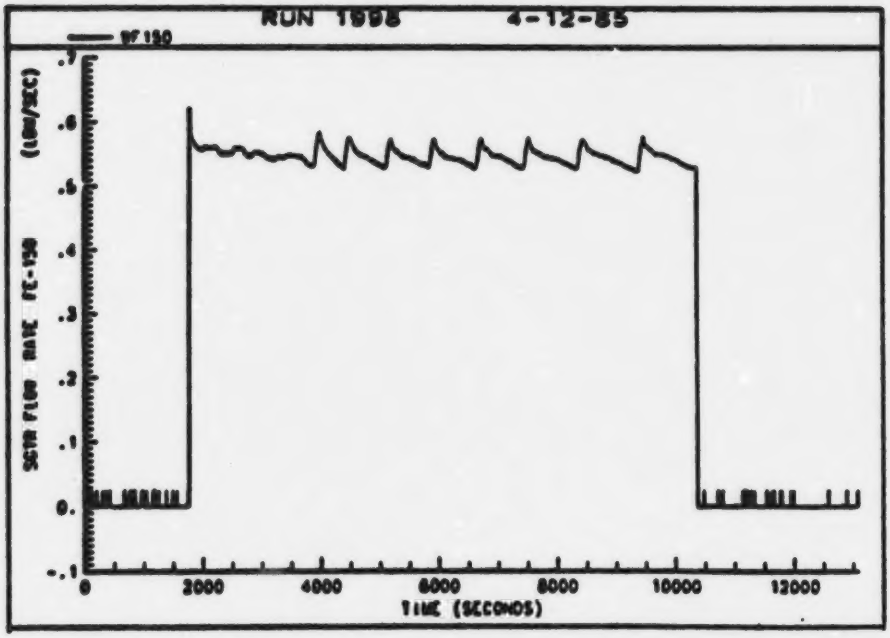

Figure 5-312. SGTR Flow Rate (WF-150): Test No. 10 (T-1998)

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356

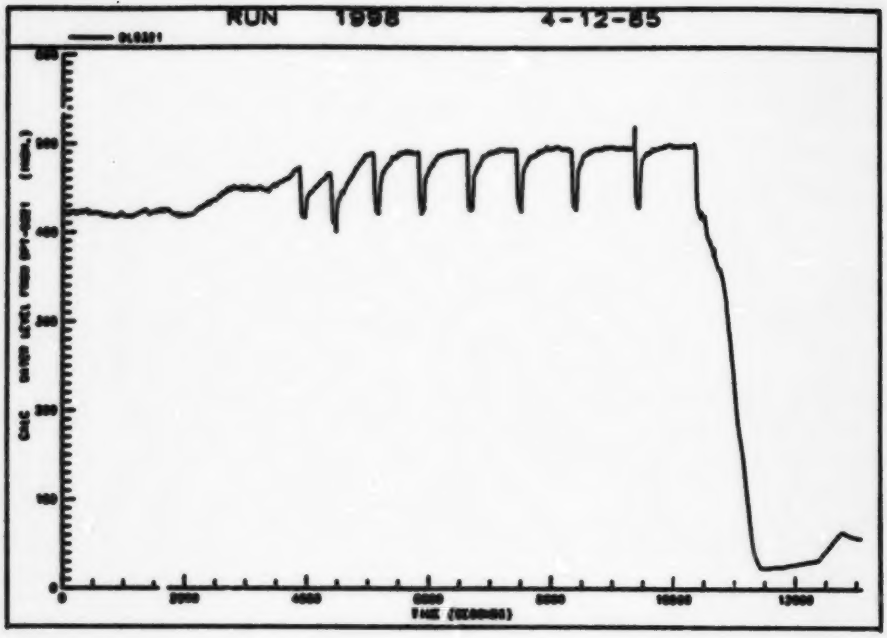

Figure 5-313. Downcomer Water Level - Wide Range (WL-9321): Test No. 10 (T-1998)

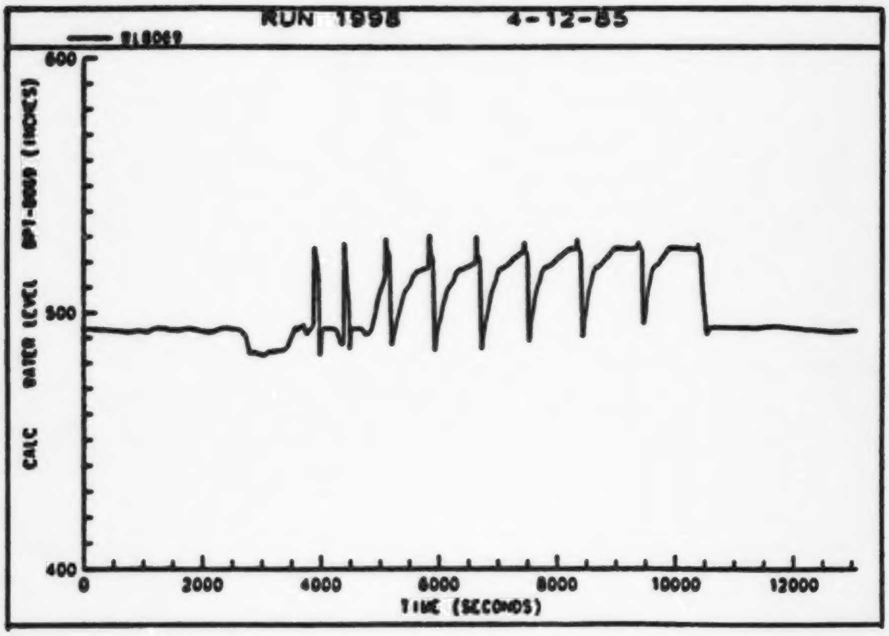

Figure 5-314. Water Level - Upper Region (WL-8069): Test No. 10 (T-1998)

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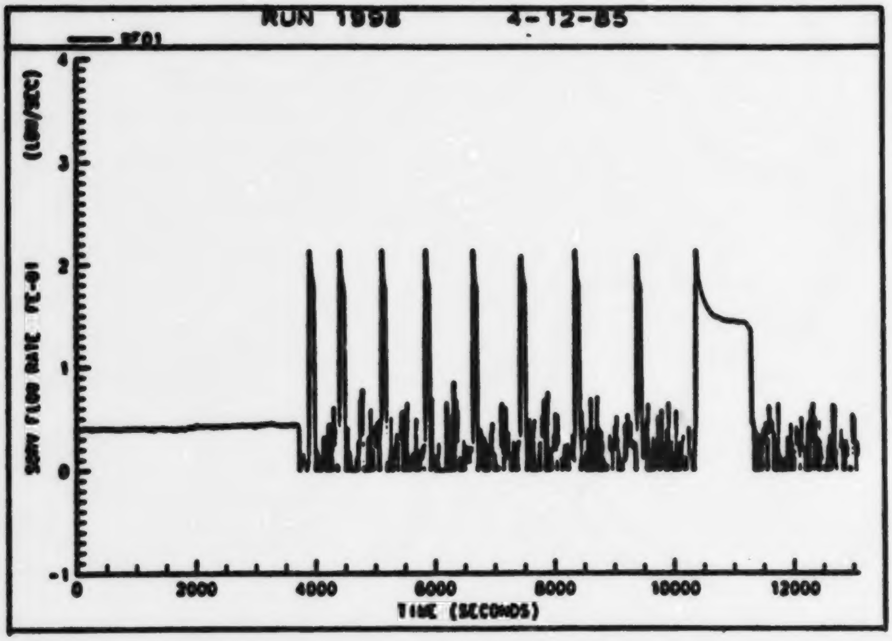

Figure 5-315. SORV Flow Rate (WF-01):
Test No. 10 (T-1998)

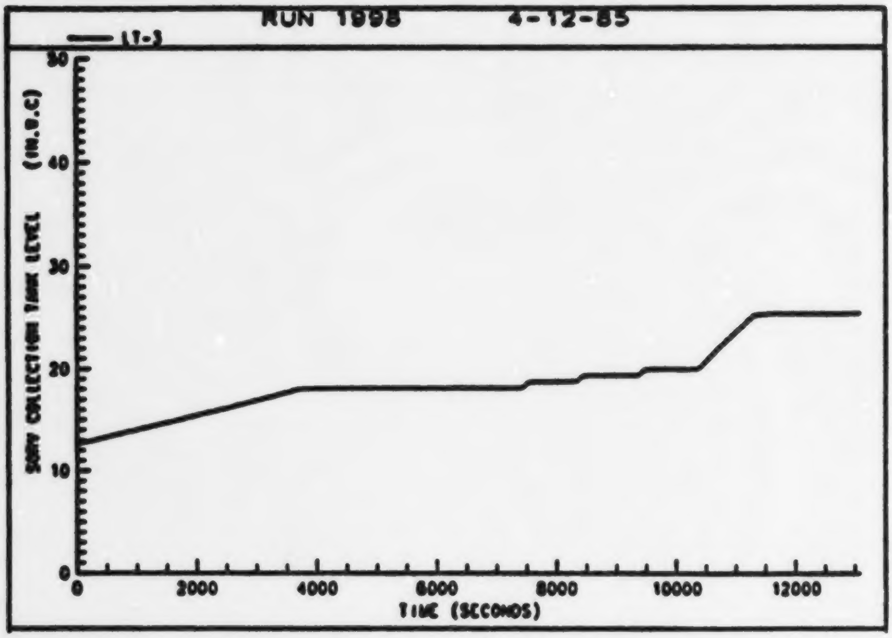

Figure 5-316. SORV Tank Level (LT-3):
Test No. 10 (T-1998)

358

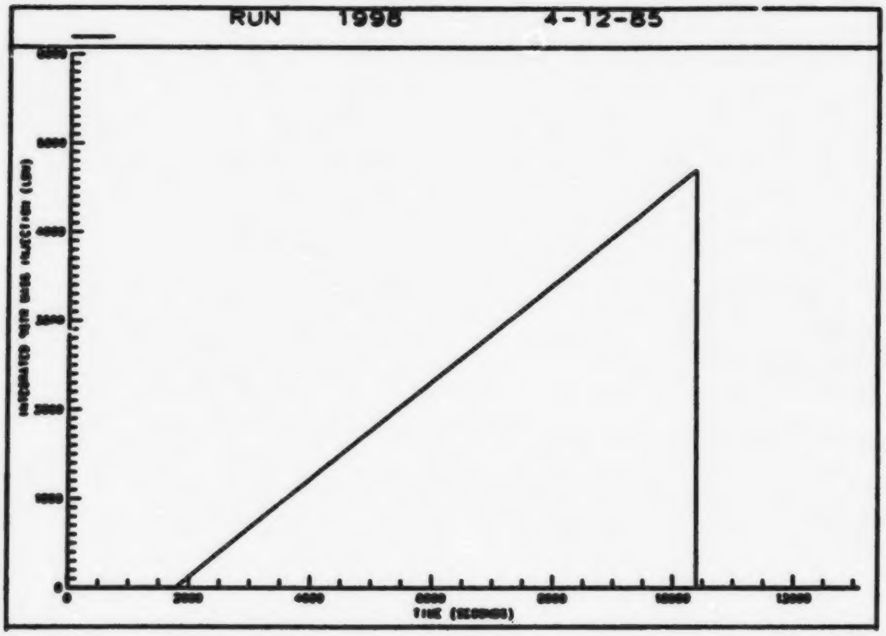

Figure 5-317. Integrated SGTR Flow: Test No. 10 (T-1998)

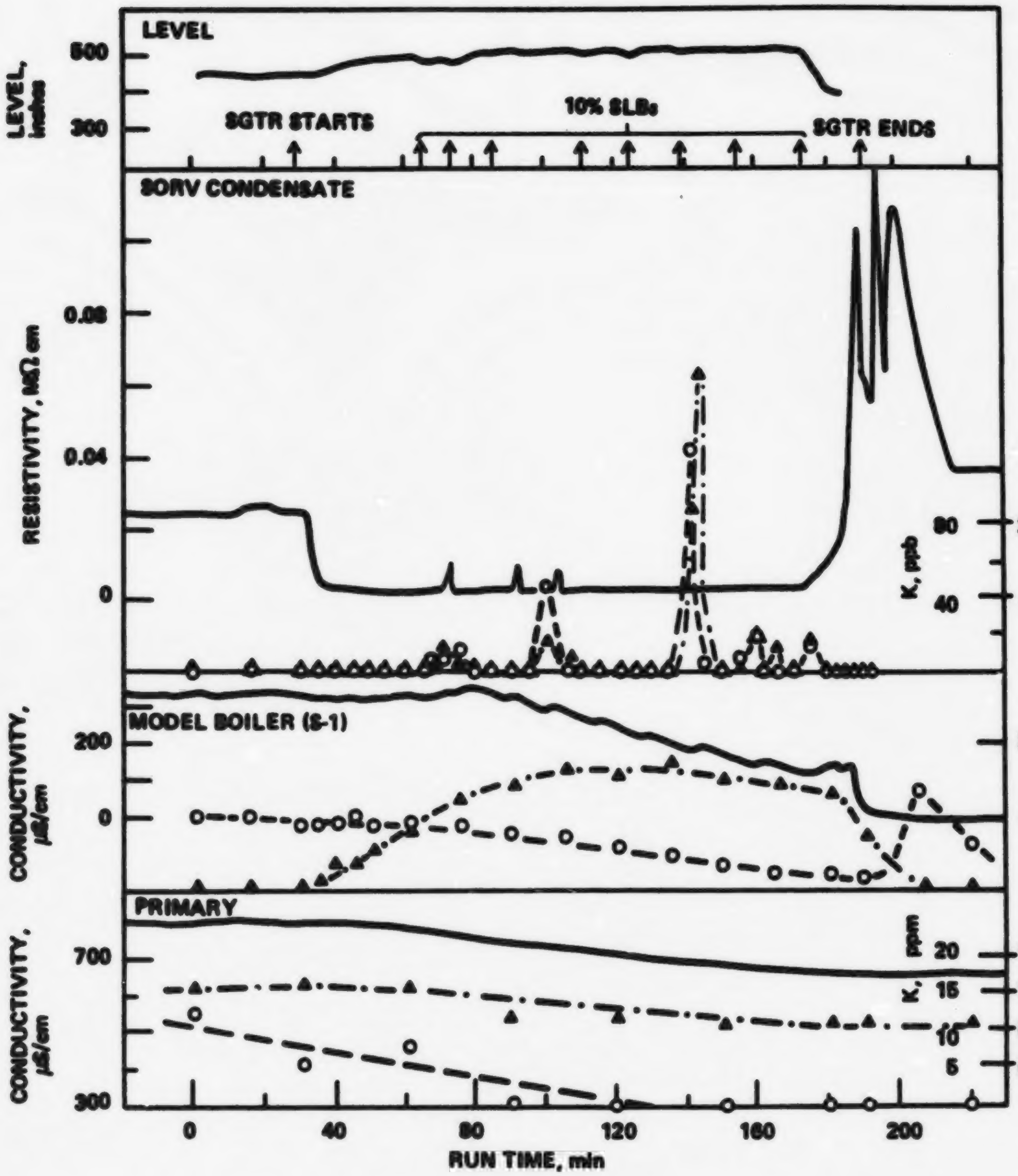

Figure 5-318. Variation in Tracer Concentrations: Test No. 10 (T-1998)

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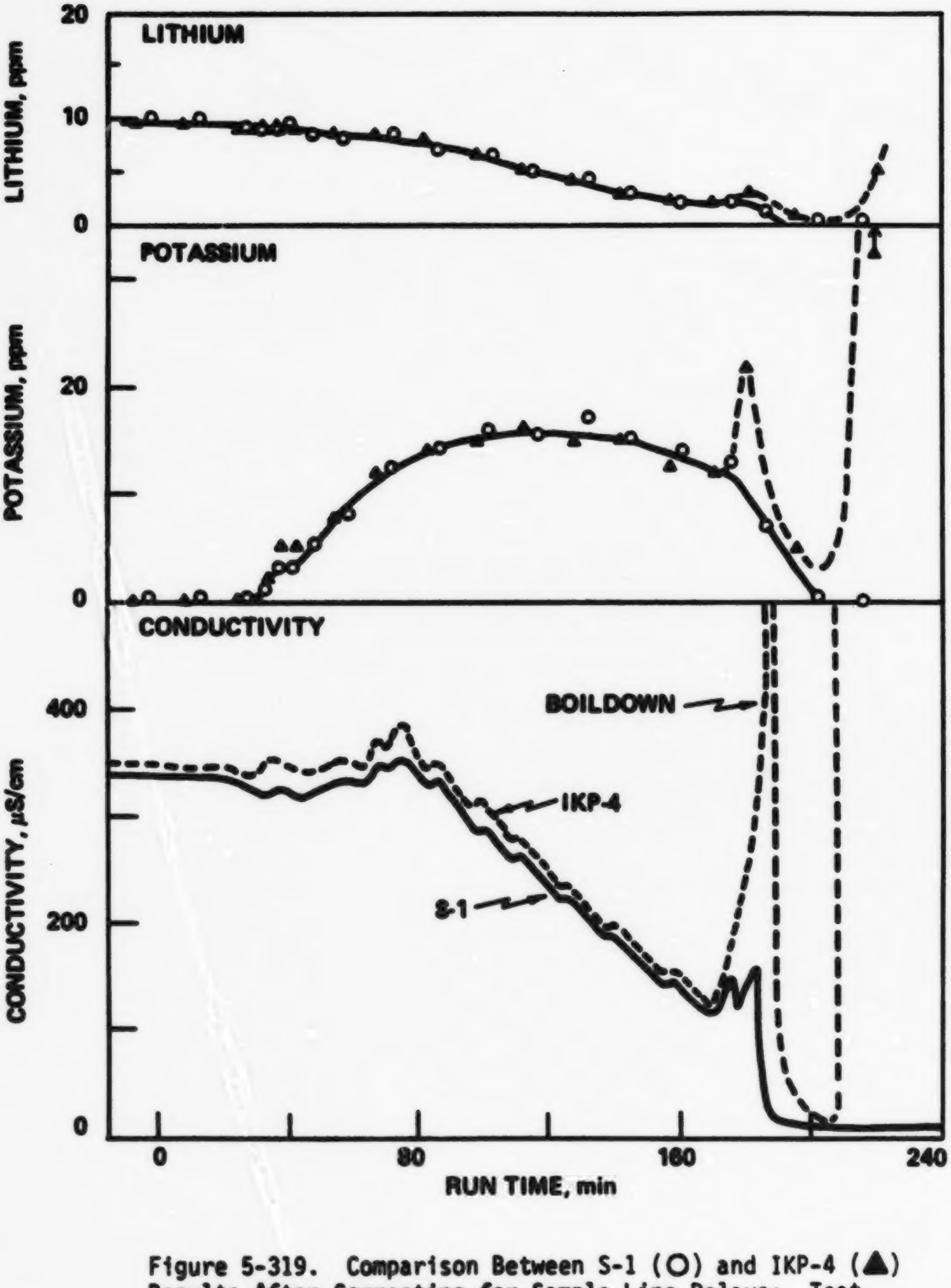

Figure 5-319. Comparison Between S-1 (○) and IKP-4 (▲) Results After Correcting for Sample Line Delays: Test No. 10 (T-1998)

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361

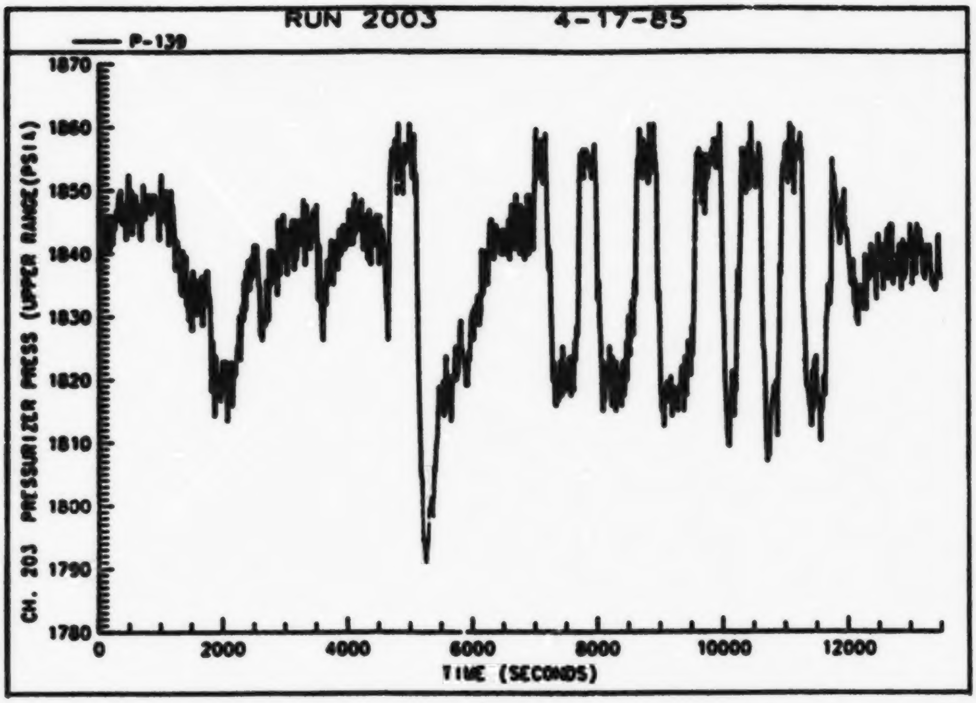

Figure 5-320. Primary System (Pressurizer) Pressure (P-139): Test No. 11 (T-2003)

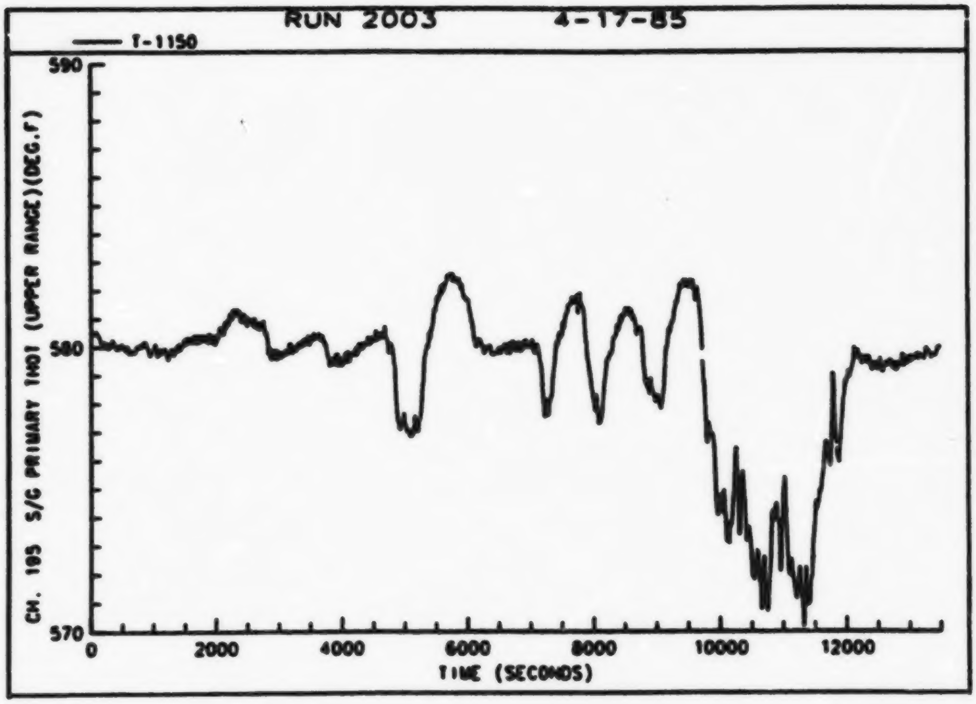

Figure 5-321. Primary Fluid T_{hot} (T-1150): Test No. 11 (T-2003)

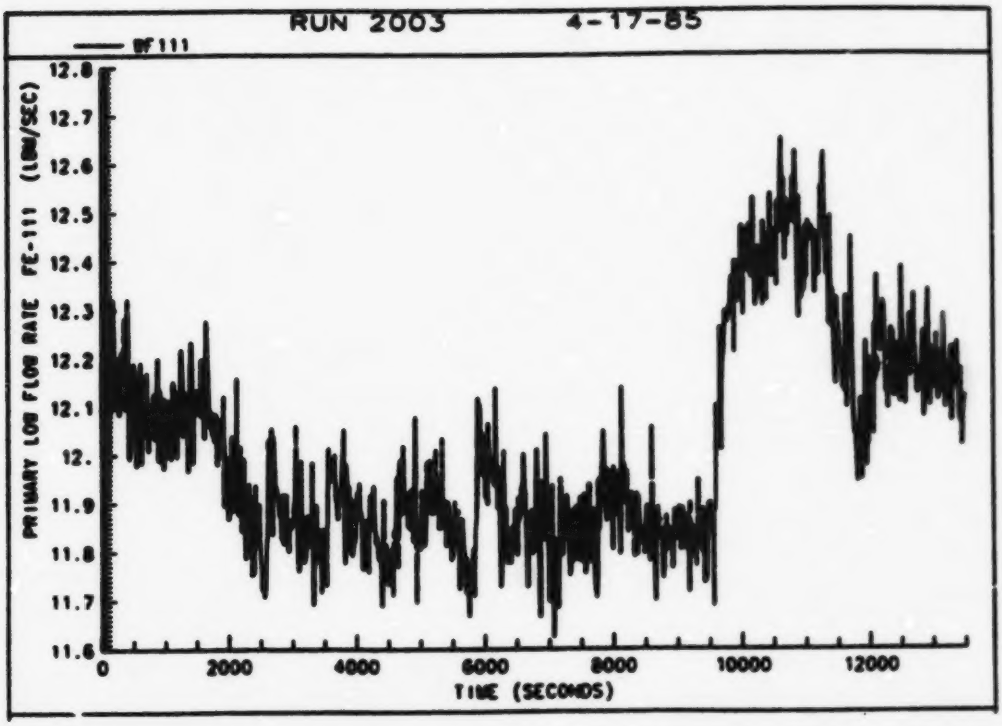

Figure 5-322. Primary Fluid Flow Rate (WF-111): Test No. 11 (T-2003)

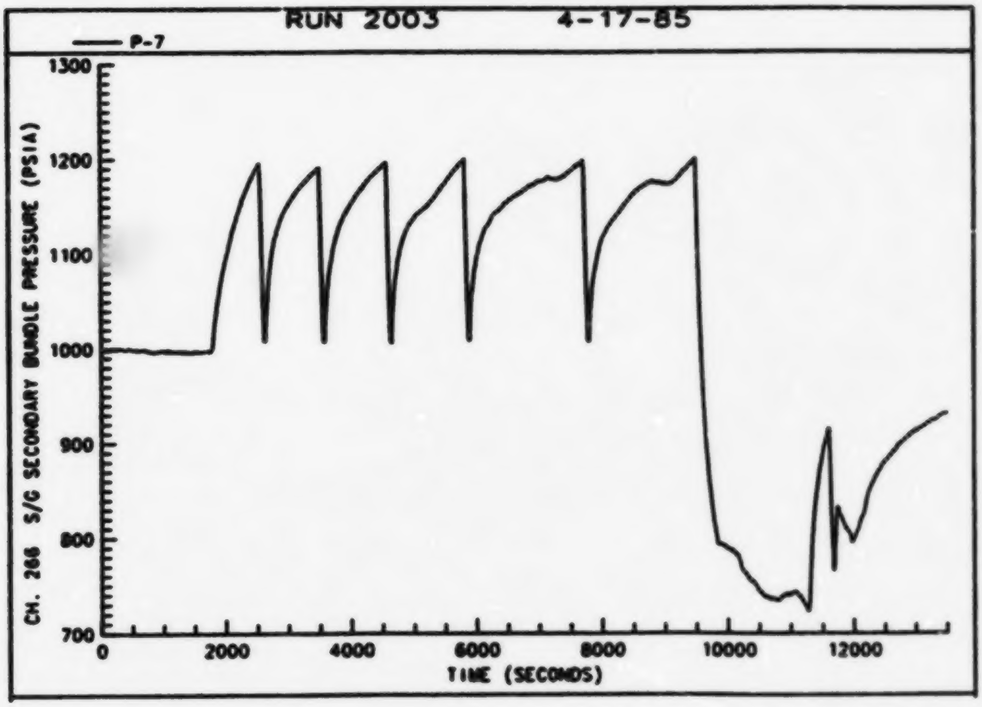

Figure 5-323. Secondary Side Pressure (P-7): Test No. 11 (T-2003)

363

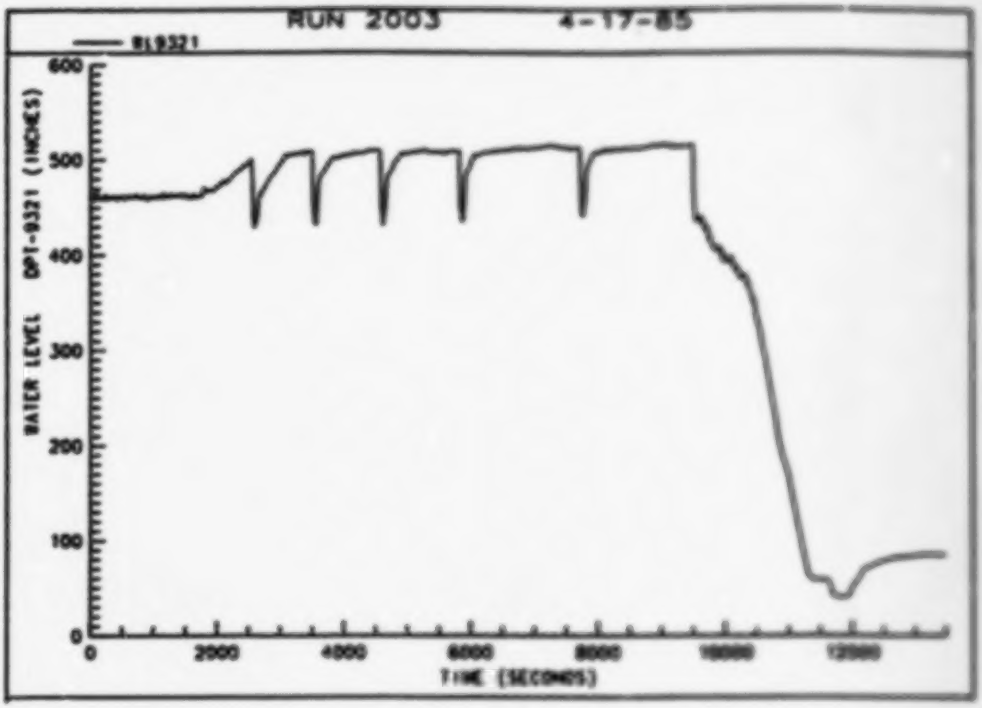

Figure 5-324. Downcomer Water Level - Wide Range (WL-9321): Test No. 11 (T-2003)

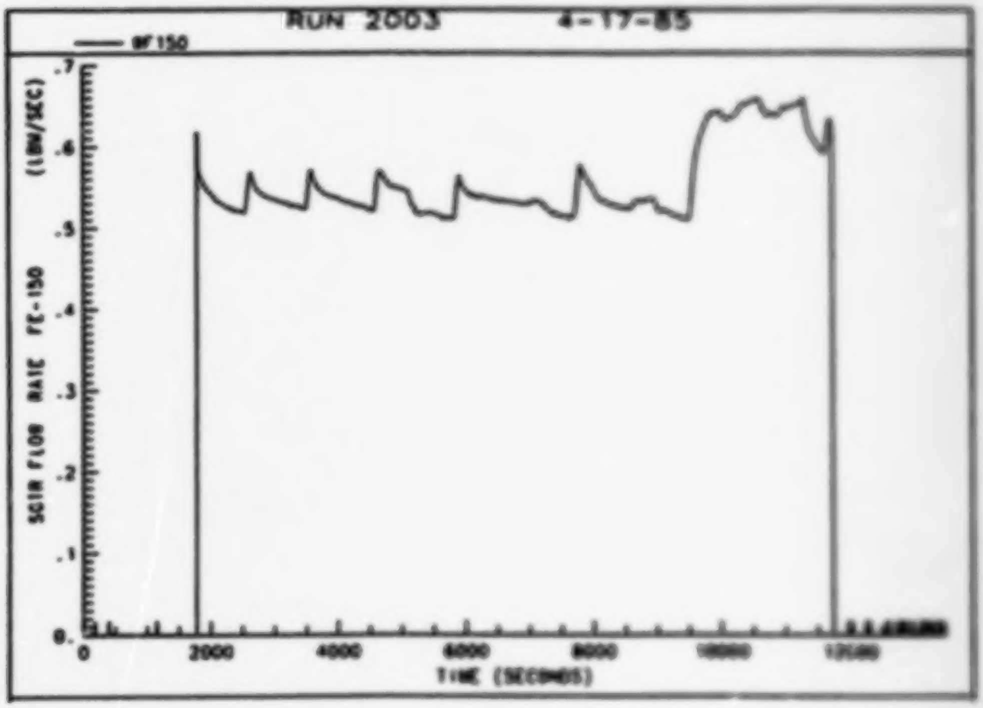

Figure 5-325. SGTR Flow Rate (WF-150): Test No. 11 (T-2003)

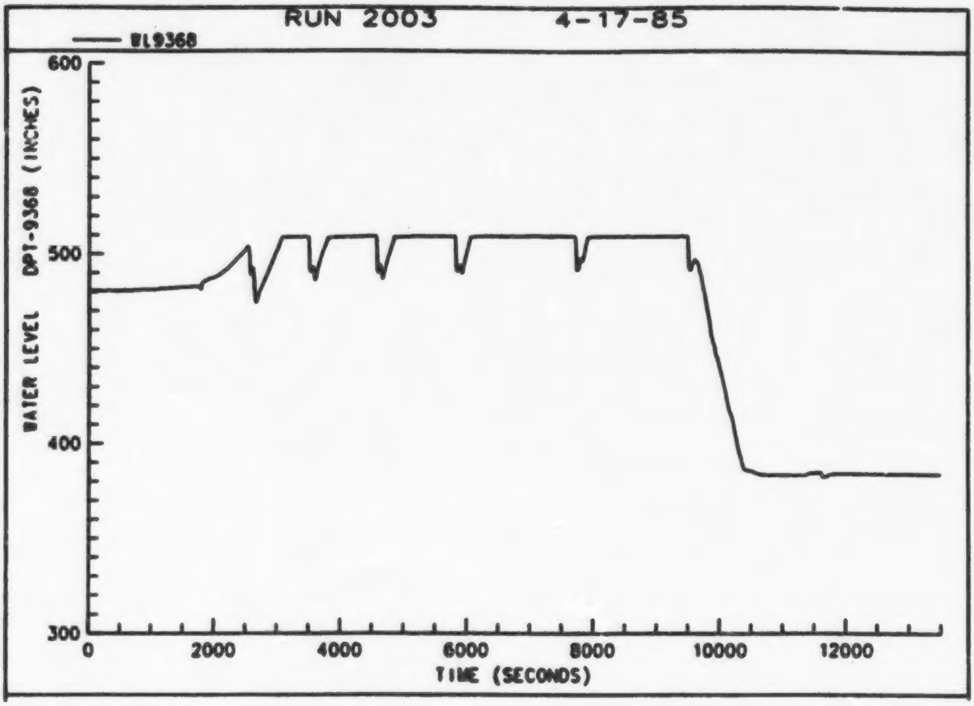

Figure 5-326. Downcomer Water Level - Narrow Range (WL-9368): Test No. 11 (T-2003)

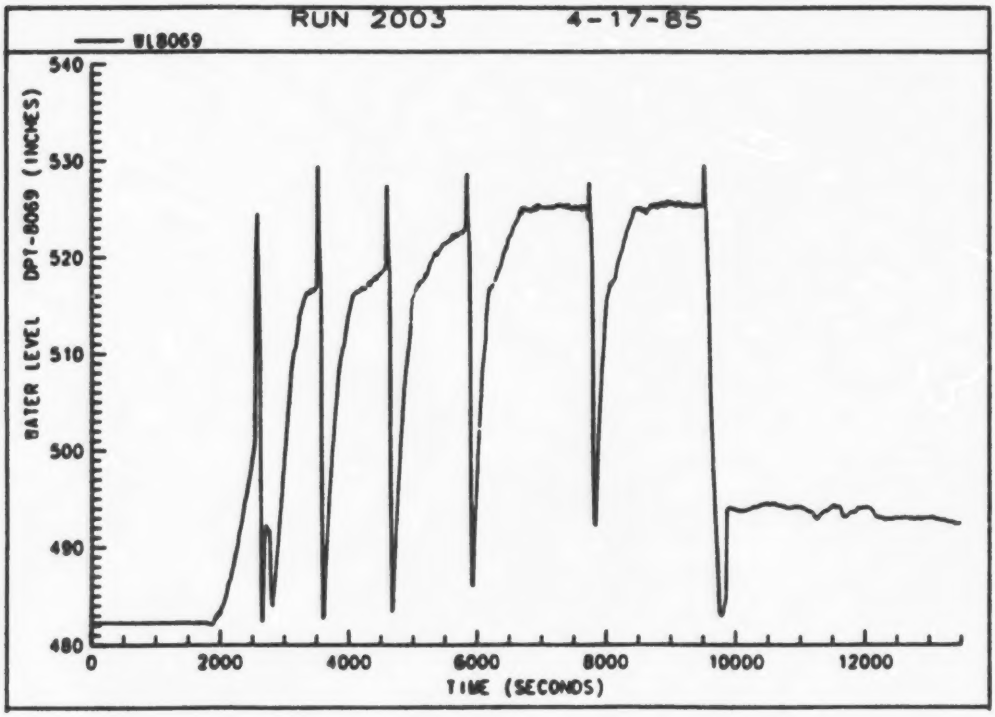

Figure 5-327. Water Level - Upper Region (WL-8069): Test No. 11 (T-2003)

365

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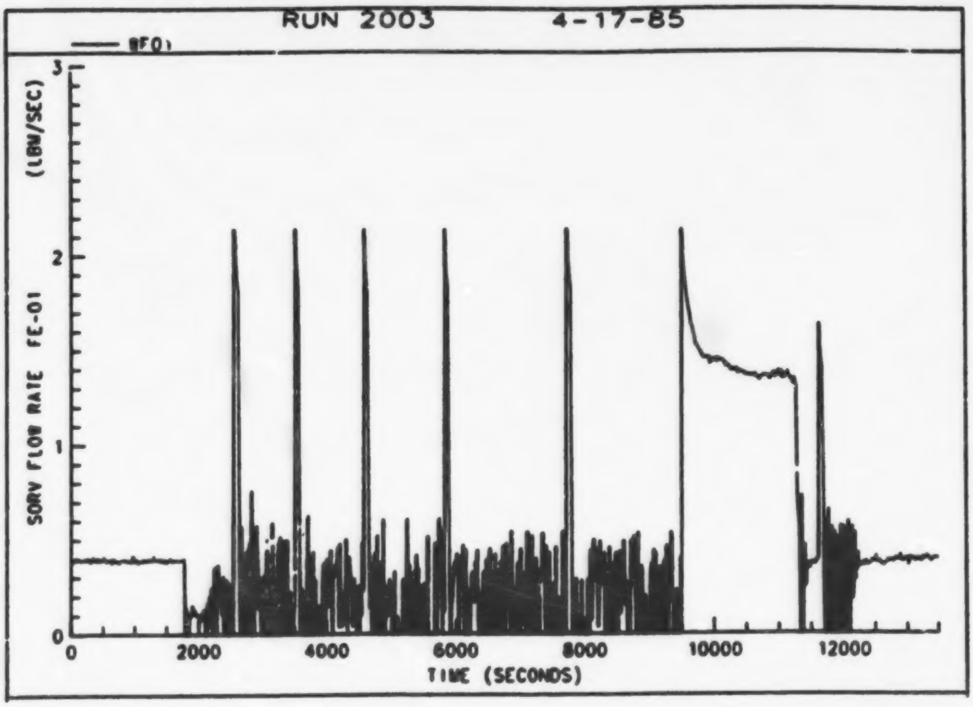

Figure 5-328. SORV Flow Rate (WF-01): Test No. 11 (T-2003)

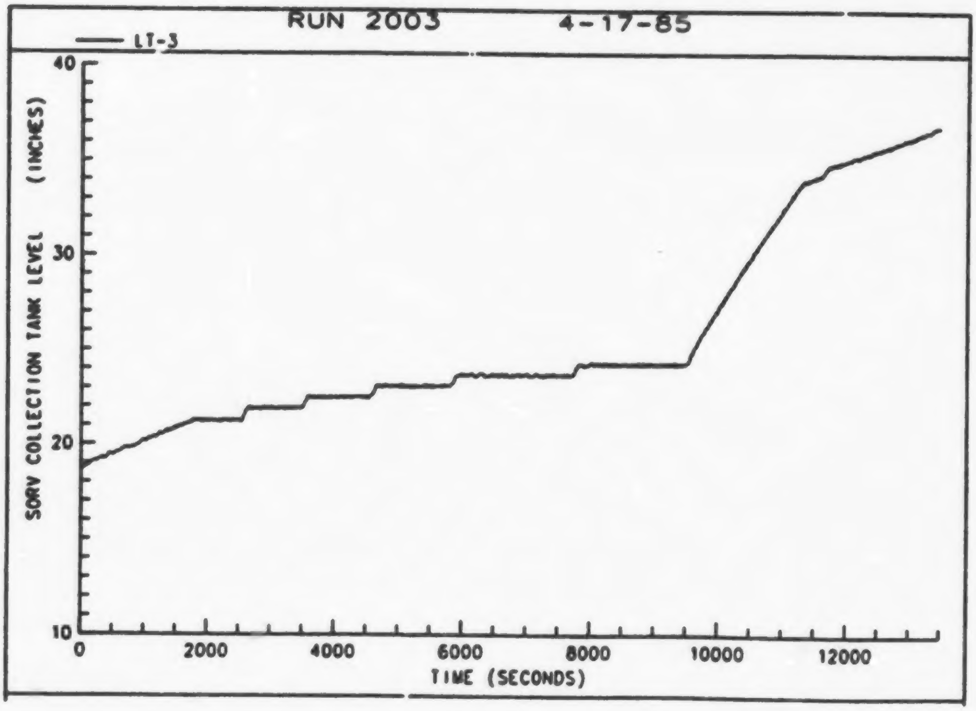

Figure 5-329. SORV Tank Level (LT-3): Test No. 11 (T-2003)

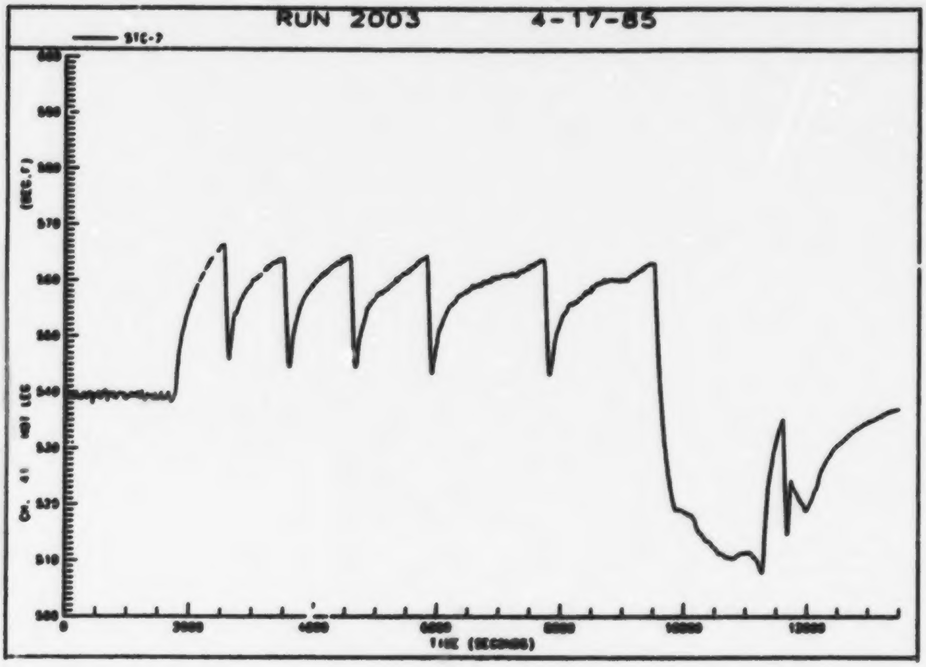

Figure 5-330. Secondary Fluid Temperature (STC-2): Test No. 11 (T-2003)

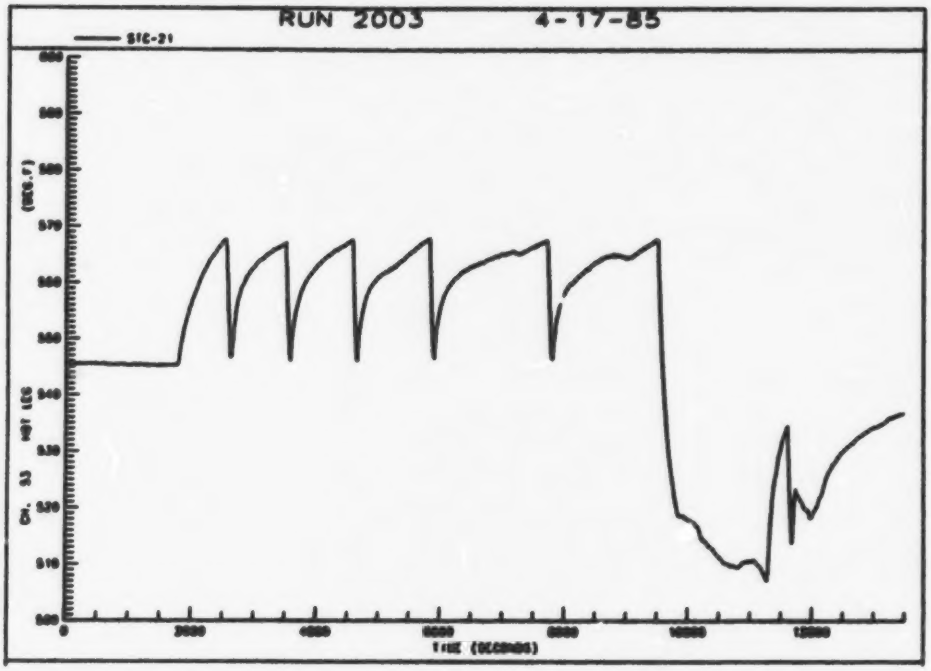

Figure 5-331. Secondary Fluid Temperature (STC-21): Test No. 11 (T-2003)

367

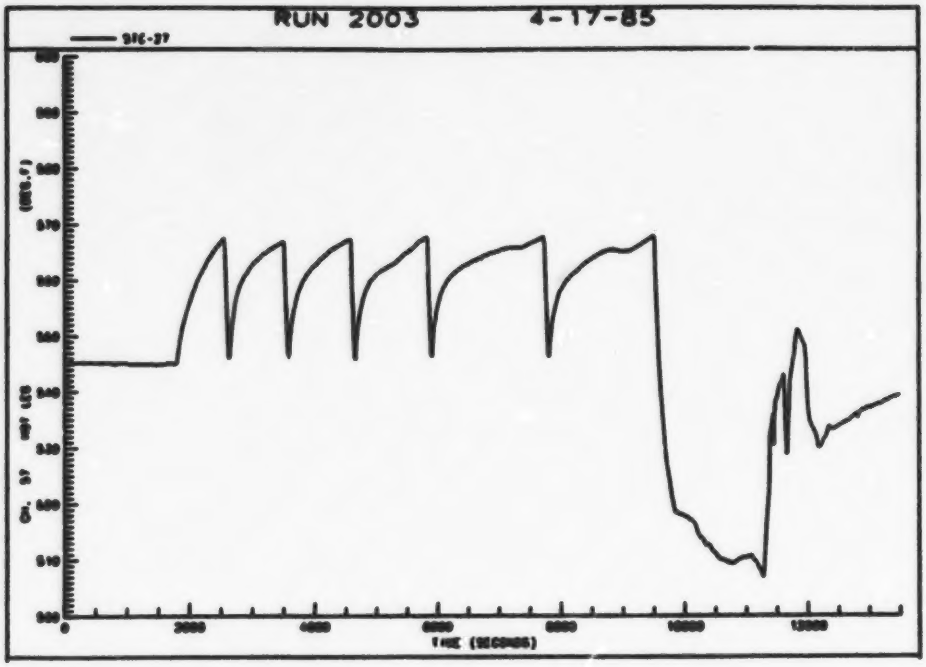

Figure 5-332. Secondary Fluid Temperature (STC-27): Test No. 11 (T-2003)

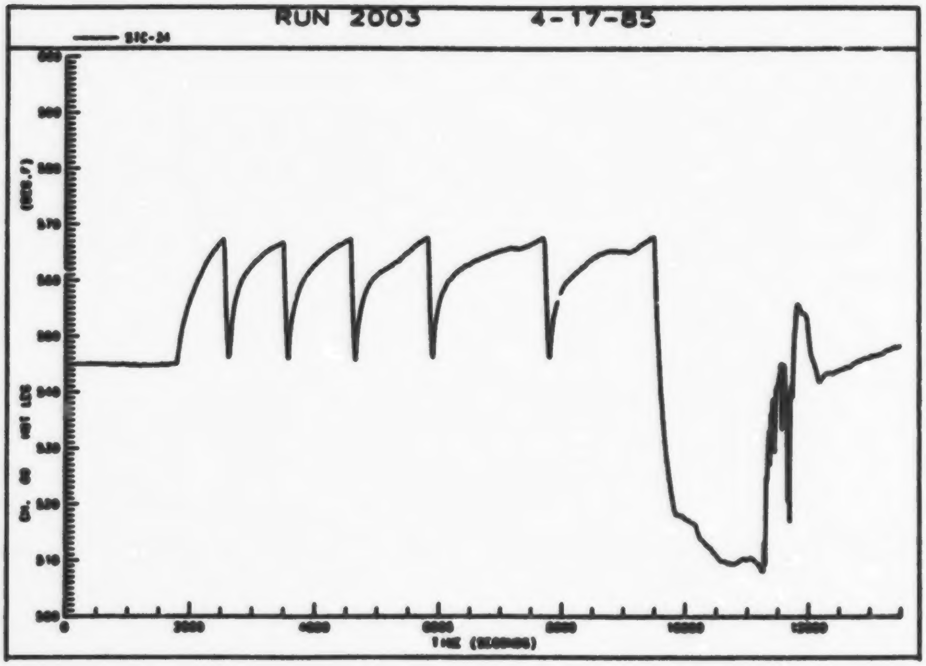

Figure 5-333. Secondary Fluid Temperature (STC-34): Test No. 11 (T-2003)

368

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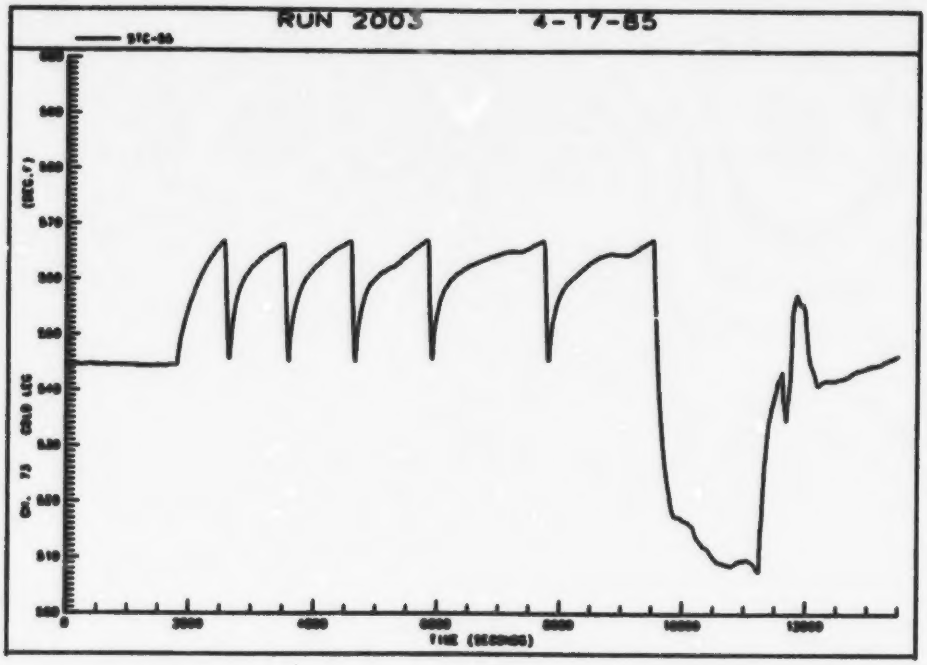

Figure 5-334. Secondary Fluid Temperature (STC-55): Test No. 11 (T-2003)

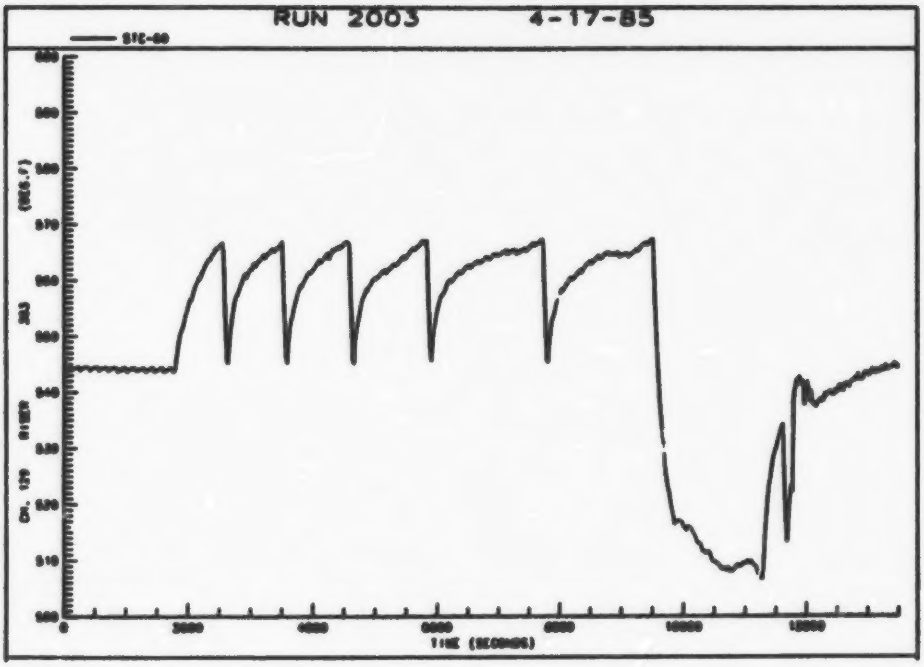

Figure 5-335. Secondary Fluid Temperature (STC-60): Test No. 11 (T-2003)

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369

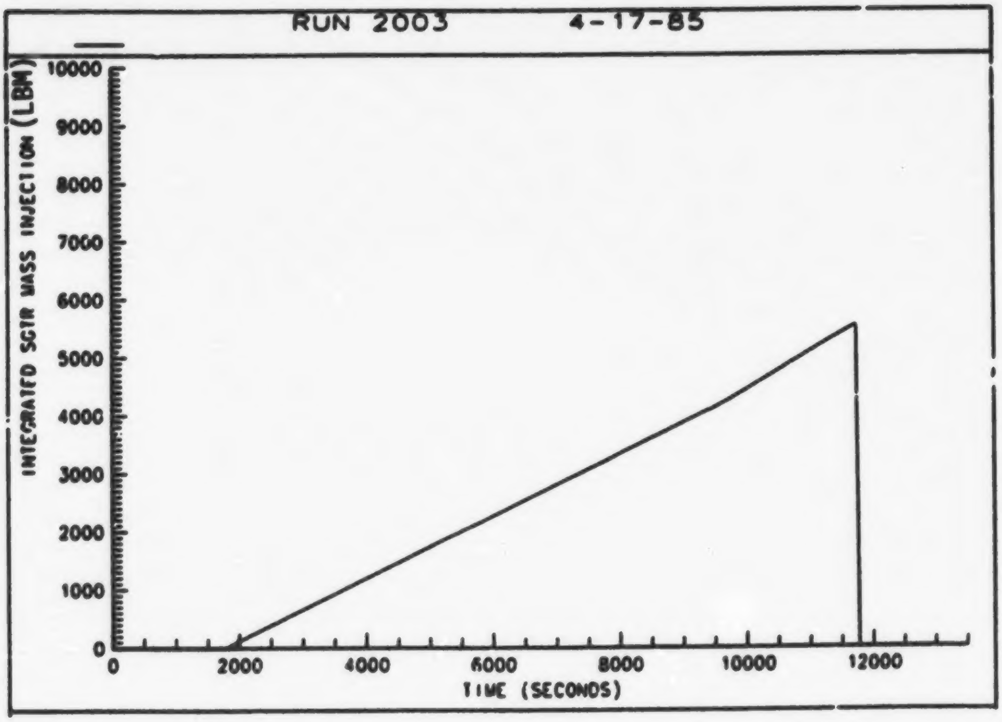

Figure 5-336. Integrated SGTR Flow: Test No. 11 (T-2003)

370

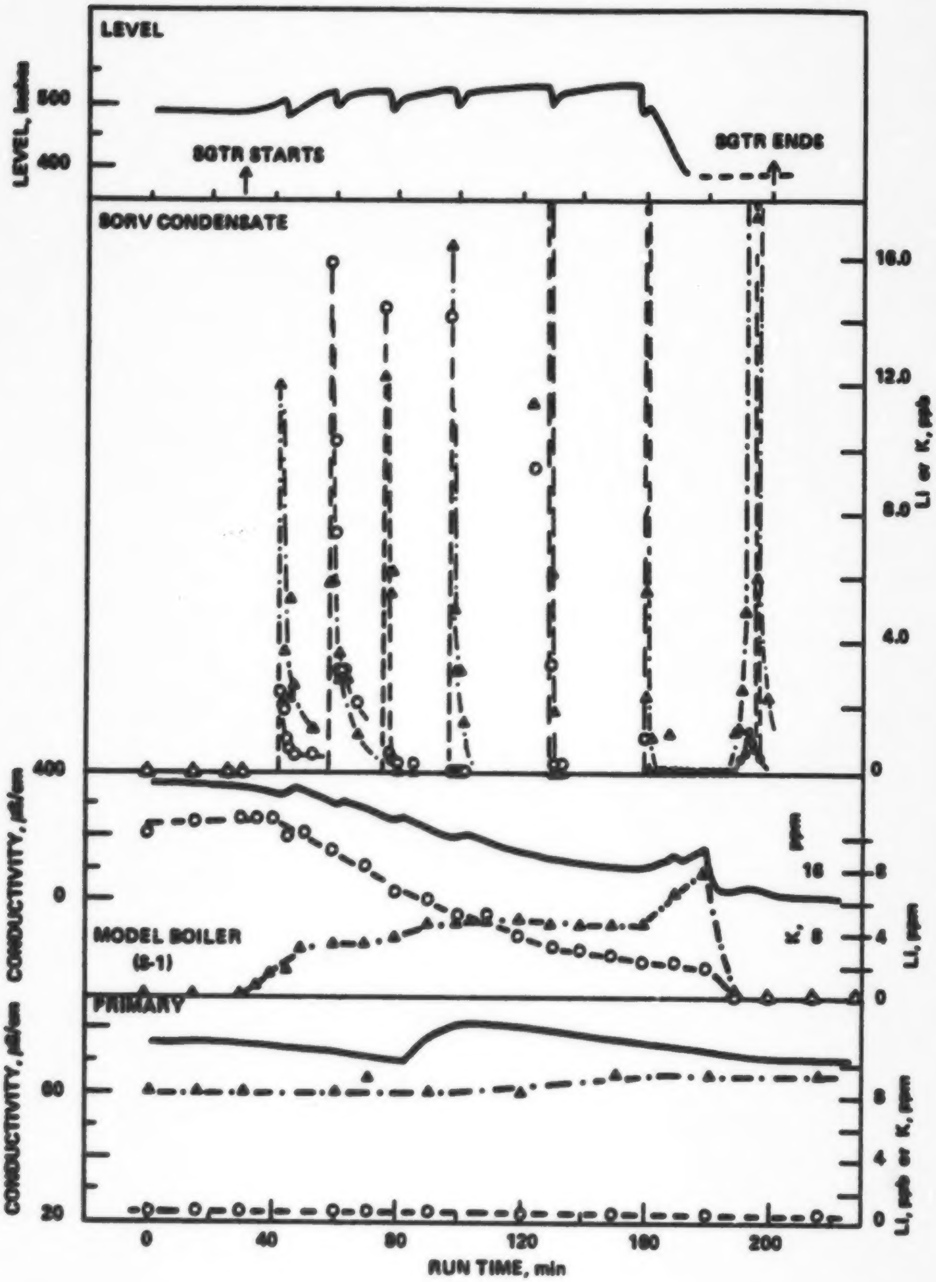

Figure 5-337. Variation in Tracer Concentrations:
Test No. 11 (T-2003)

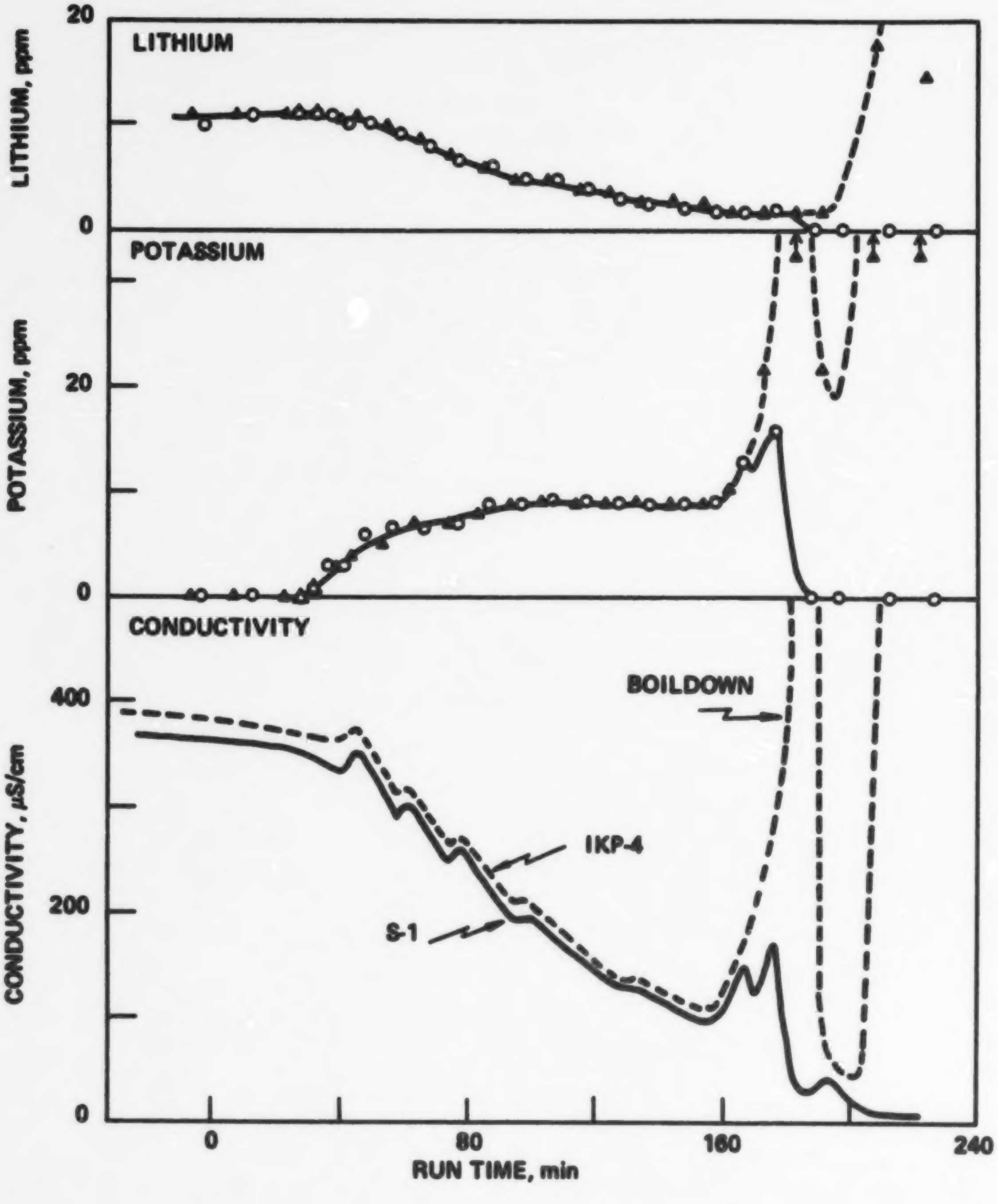

Figure 5-338. Comparison of S-1 (○) and IKP-4 (▲) Results After Correcting for Sample Line Delays: Test No. 11 (T-2003)

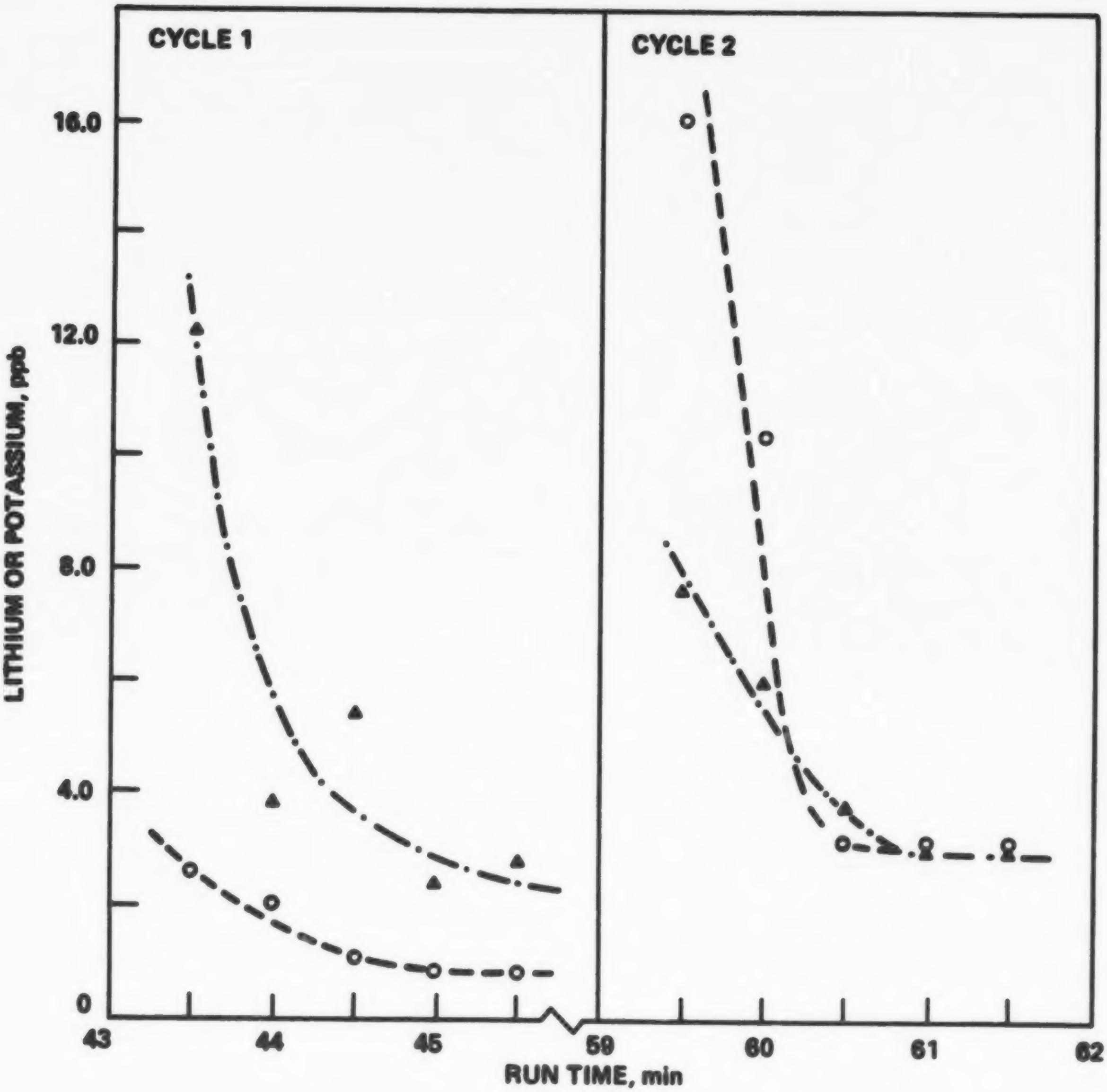

Figure 5-339. Variation in SORV Condensate Lithium (○) and Potassium (▲) Concentrations: Pressure Relief Cycles 1 and 2, Test No. 12 (T-2003)

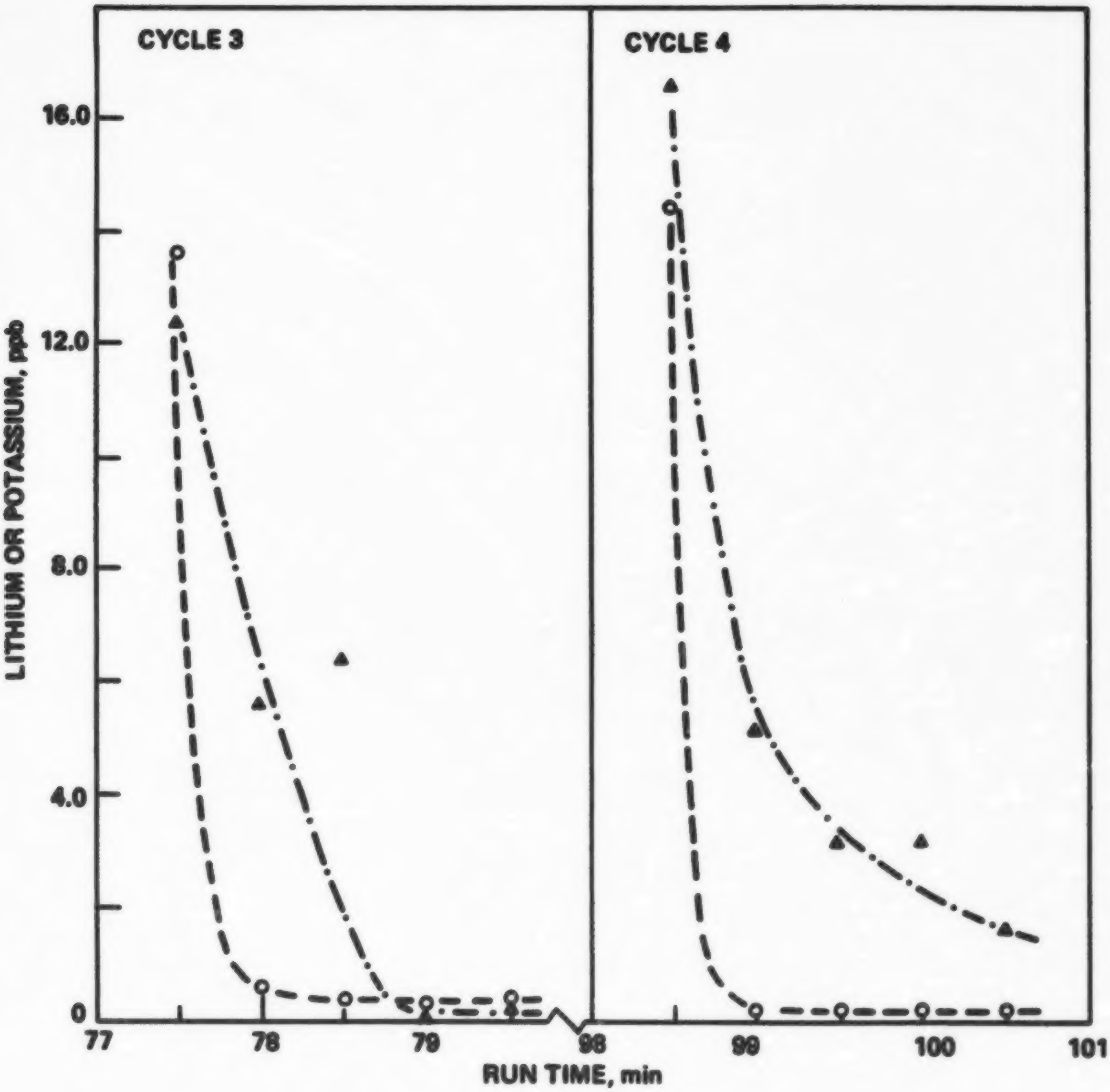

Figure 5-340. Variations in SORV Condensate Lithium (○) and Potassium (▲) Concentrations: Pressure Relief Cycles 3 and 4, Test No. 12 (T-2003)

374

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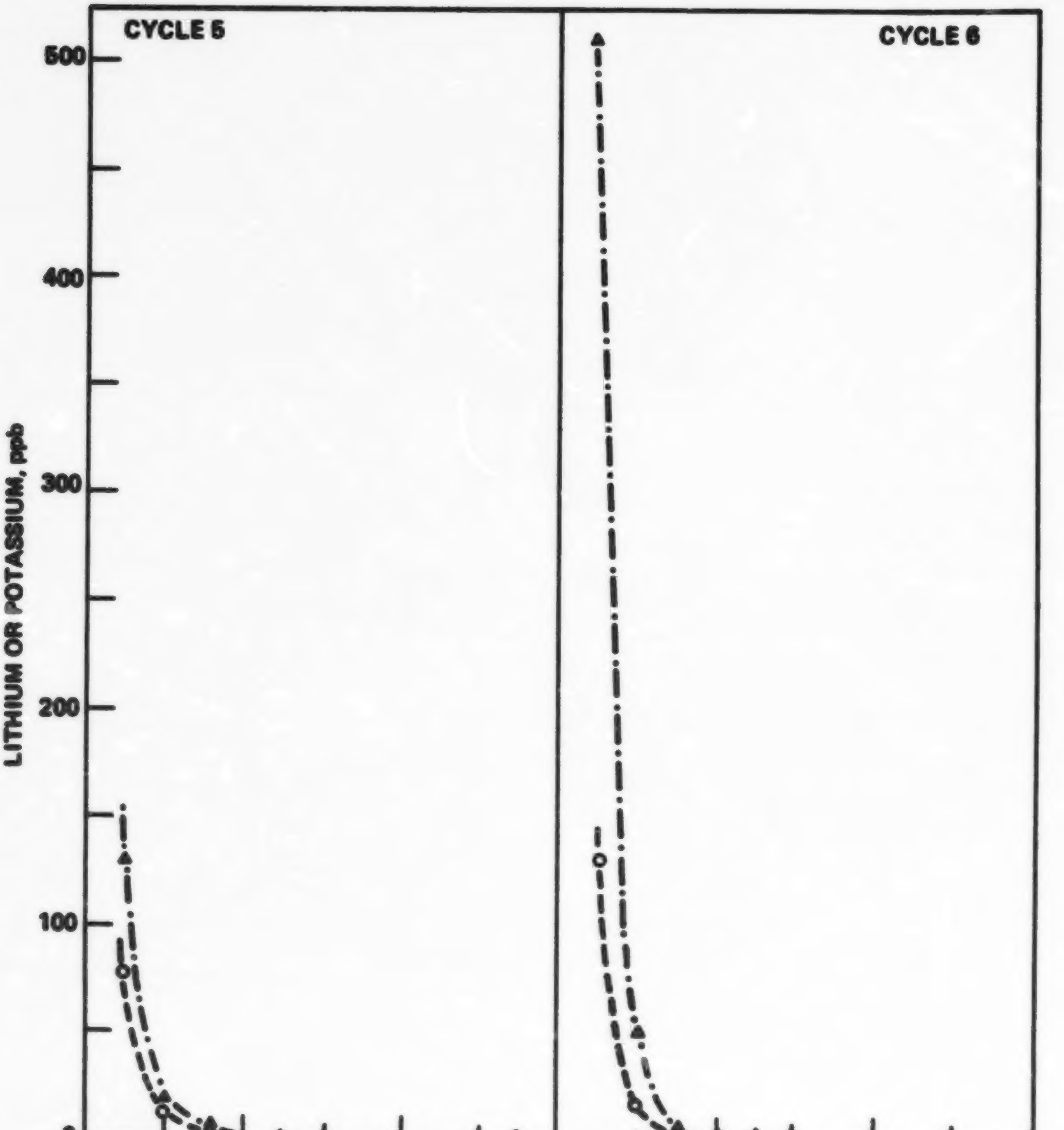

Figure 5-341. Variation in SORV Condensate Lithium (○) and Potassium (▲) Concentrations: Pressure Relief Cycles 5 and 6, Test No. 11 (T-2003)

375

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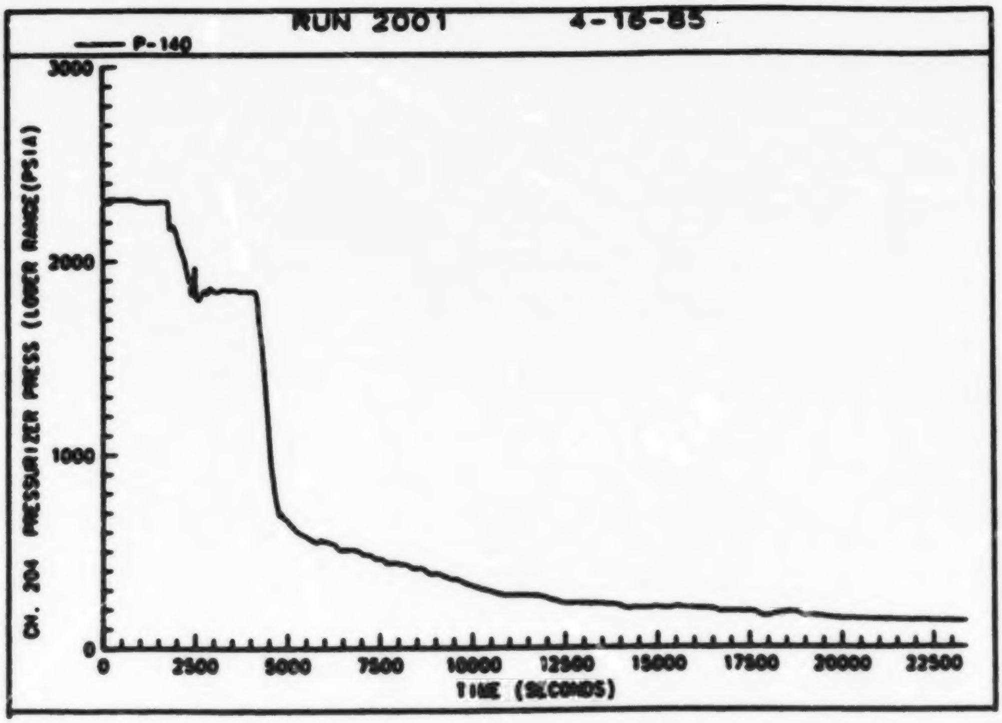

Figure 5-342. Primary System (Pressurizer) Pressure (P-140): Test No. 12 (T-2001)

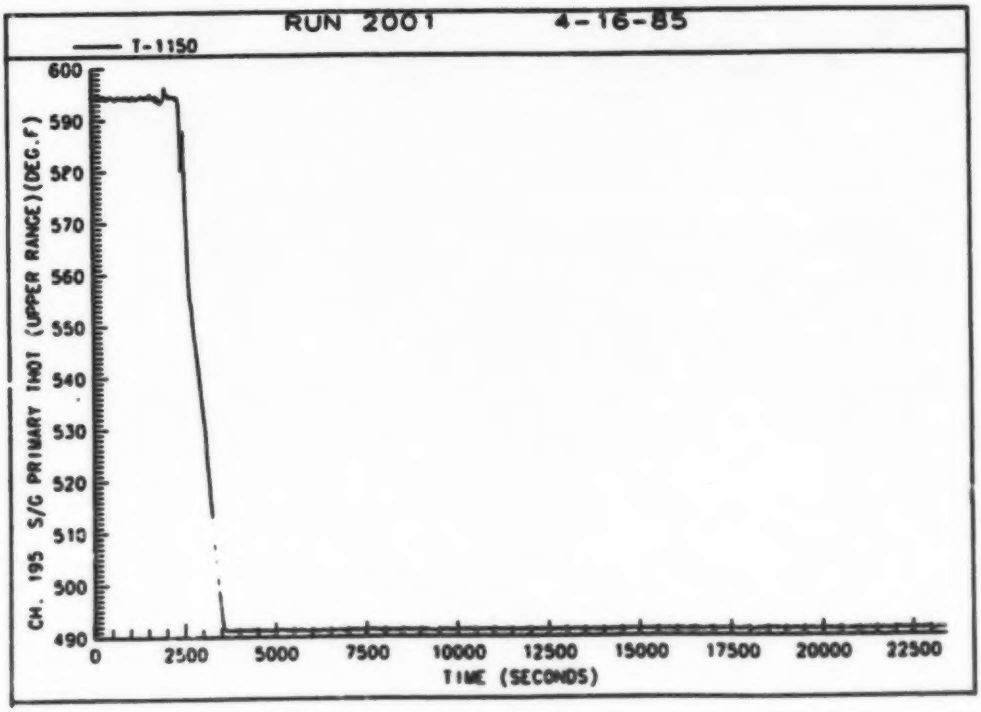

Figure 5-343. Primary Fluid T_{hot} (T-1150): Test No. 12 (T-2001)

376

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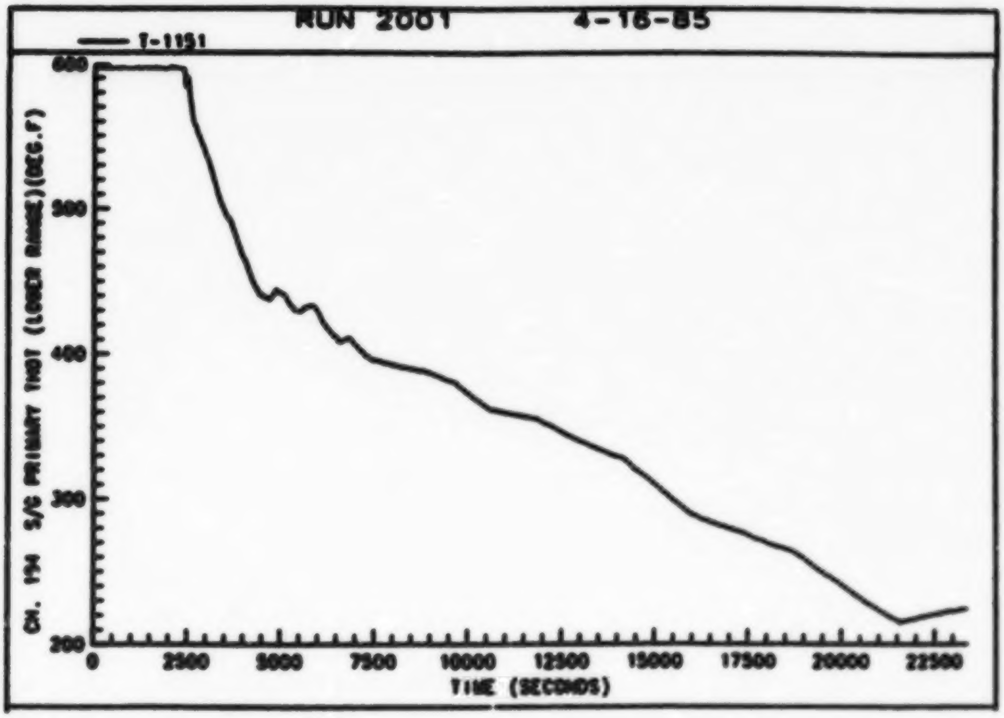

Figure 5-344. Primary Fluid T_{hot} (T-1151): Test No. 12 (T-2001)

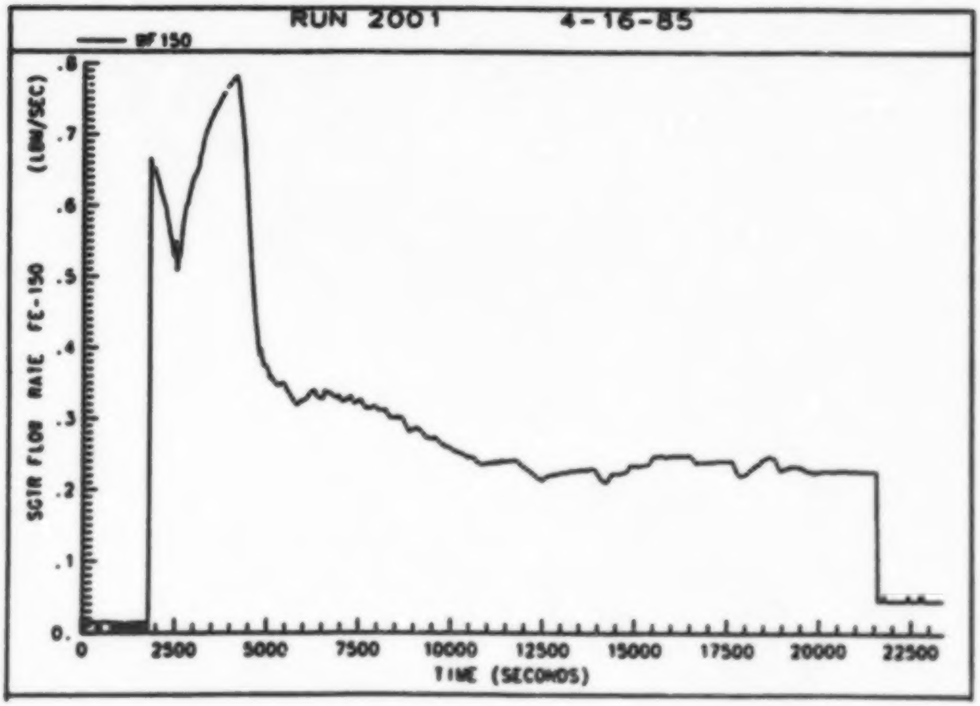

Figure 5-345. SGTR Flow Rate (WF-150): Test No. 12 (T-2001)

377

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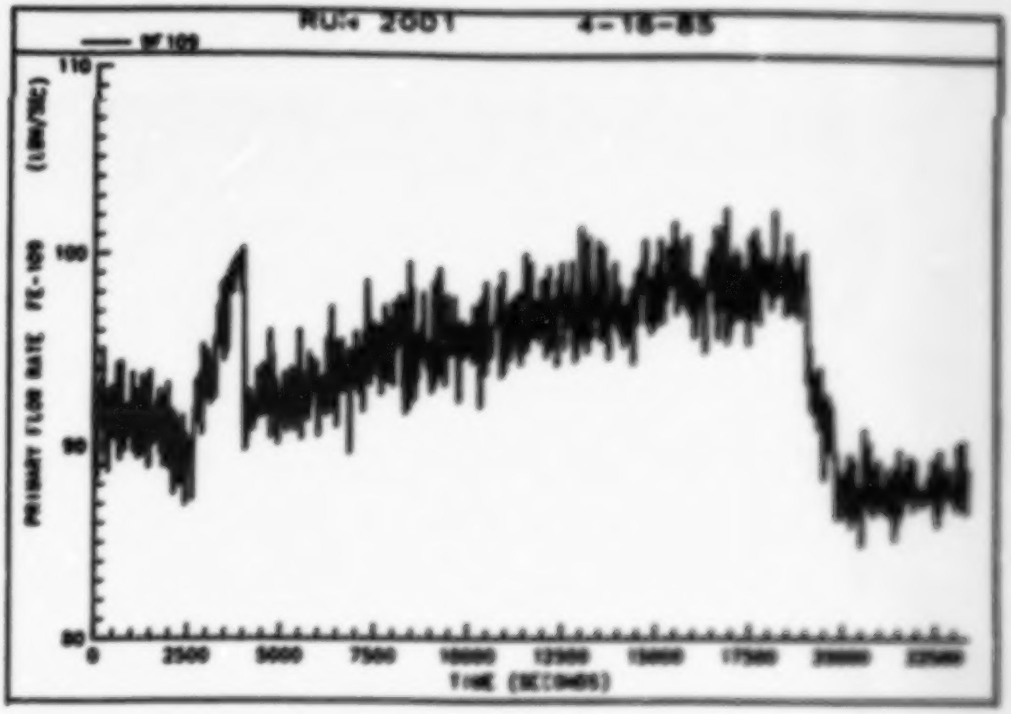

Figure 5-346. Primary Fluid Flow Rate (WF-109): Test No. 12 (T-2001)

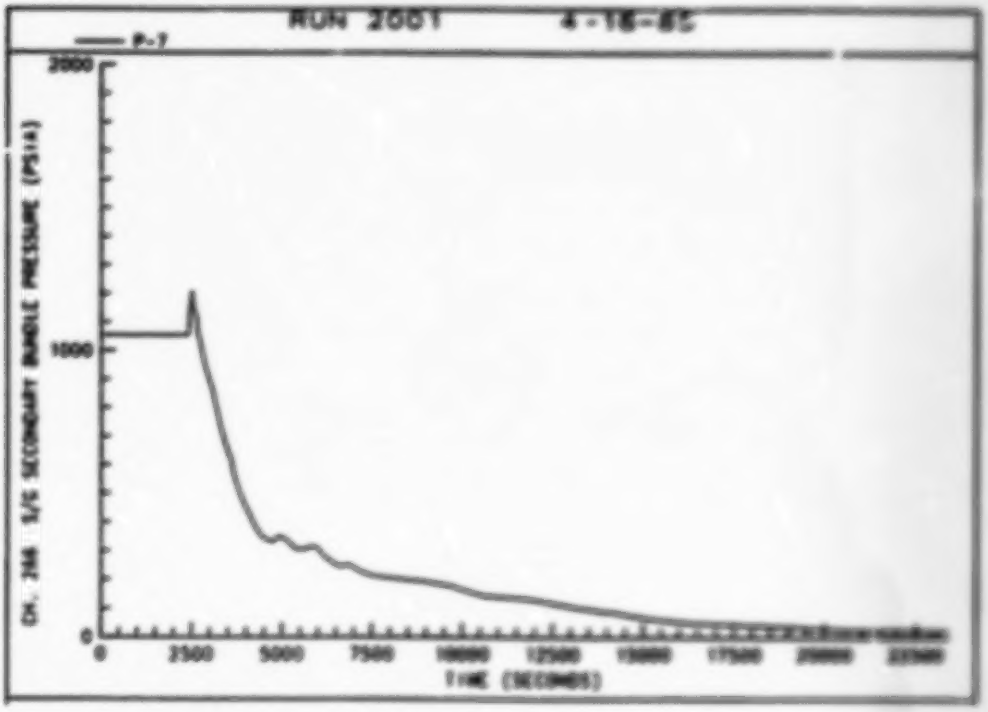

Figure 5-347. Secondary Side Prussure (P-7): Test No. 12 (T-2001)

318

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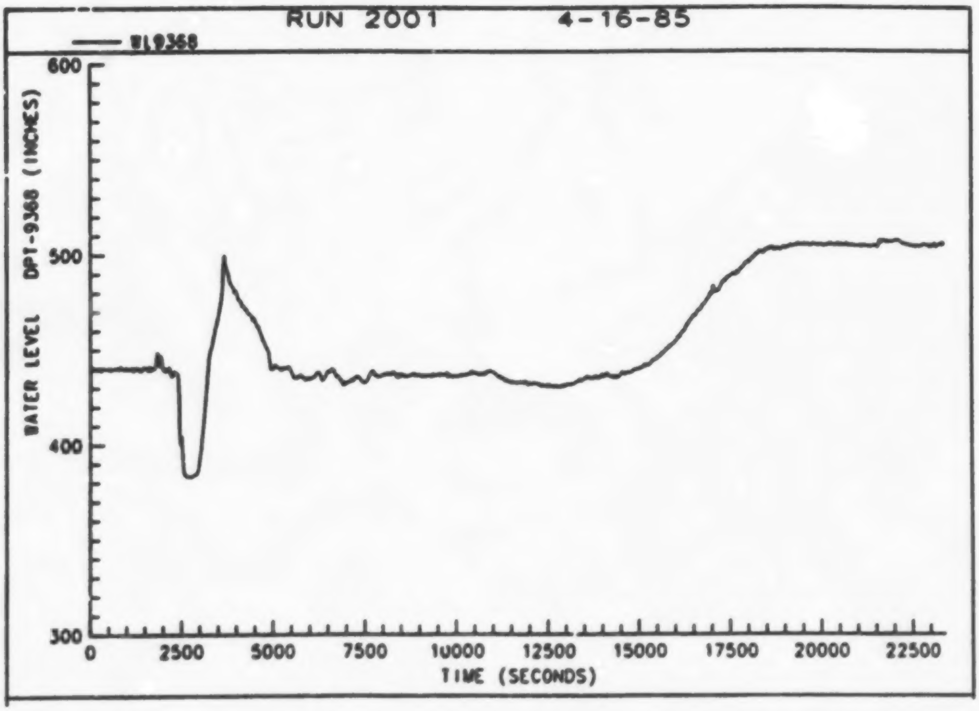

Figure 5-348. Downcomer Water Level - Narrow Range (WL-9368): Test No. 12 (T-2001)

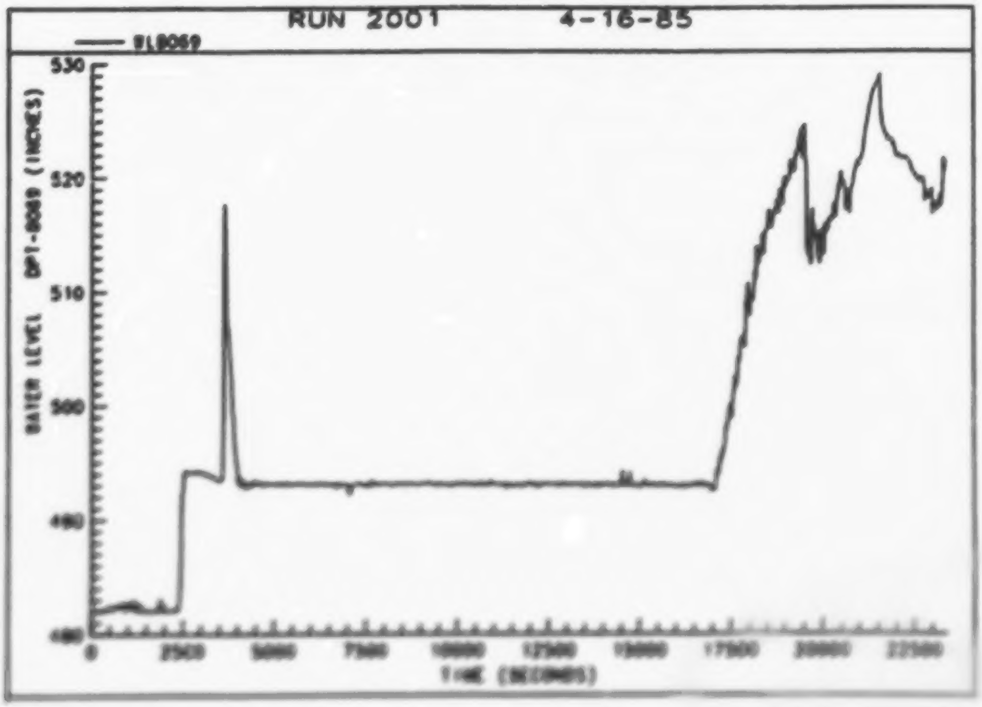

Figure 5-349. Water Level - Upper Region (WL-8069): Test No. 12 (T-2001)

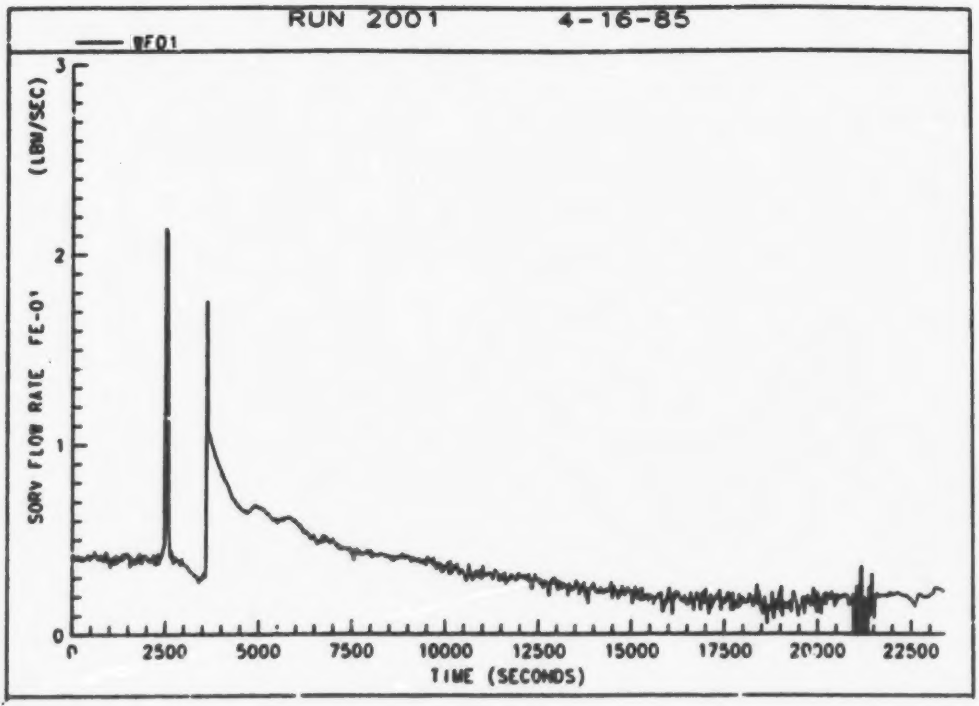

Figure 5-350. SORV Flow Rate (WF-01): Test No. 12 (T-2001)

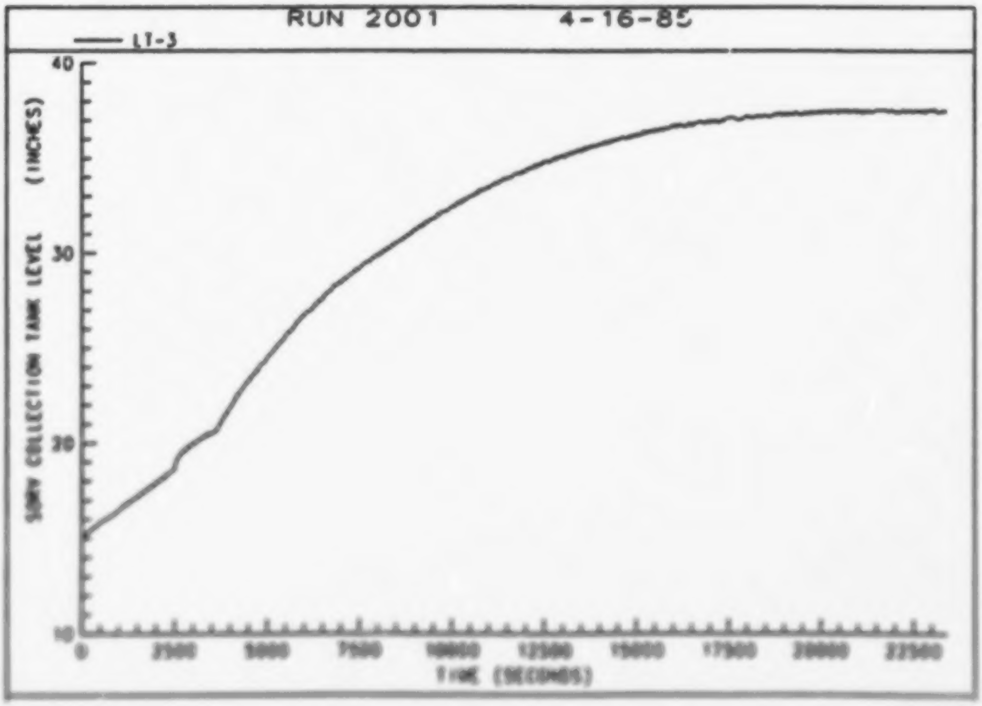

Figure 5-351. SORV Tank Level (LT-3): Test No. 12 (T-2001)

380

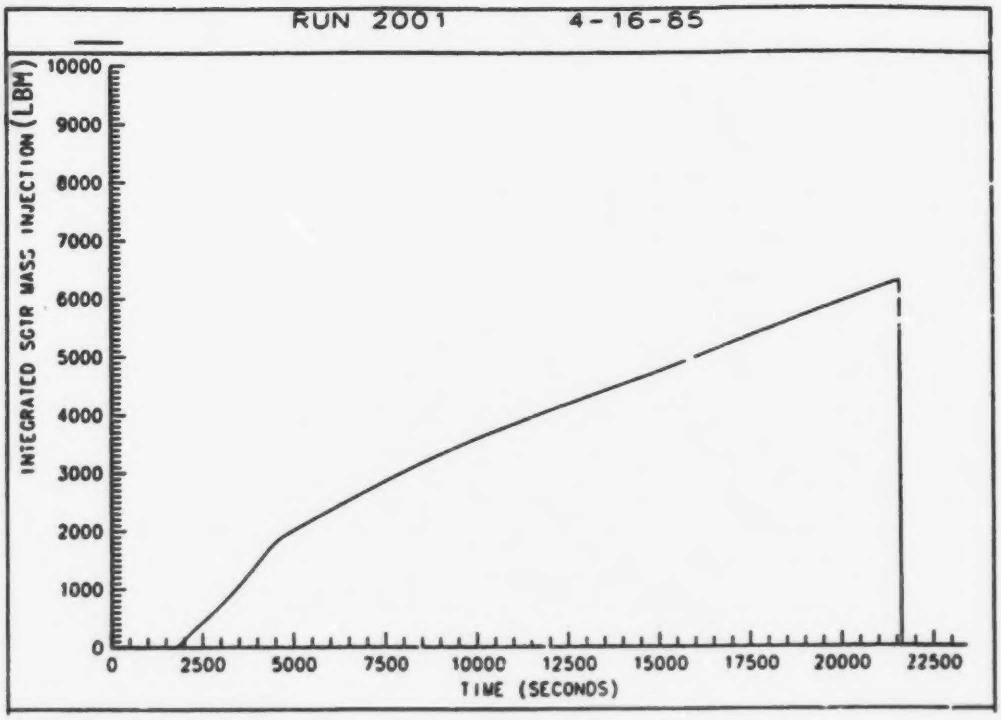

Figure 5-352. Integrated SGTR Flow: Test No. 12 (T-2001)

381

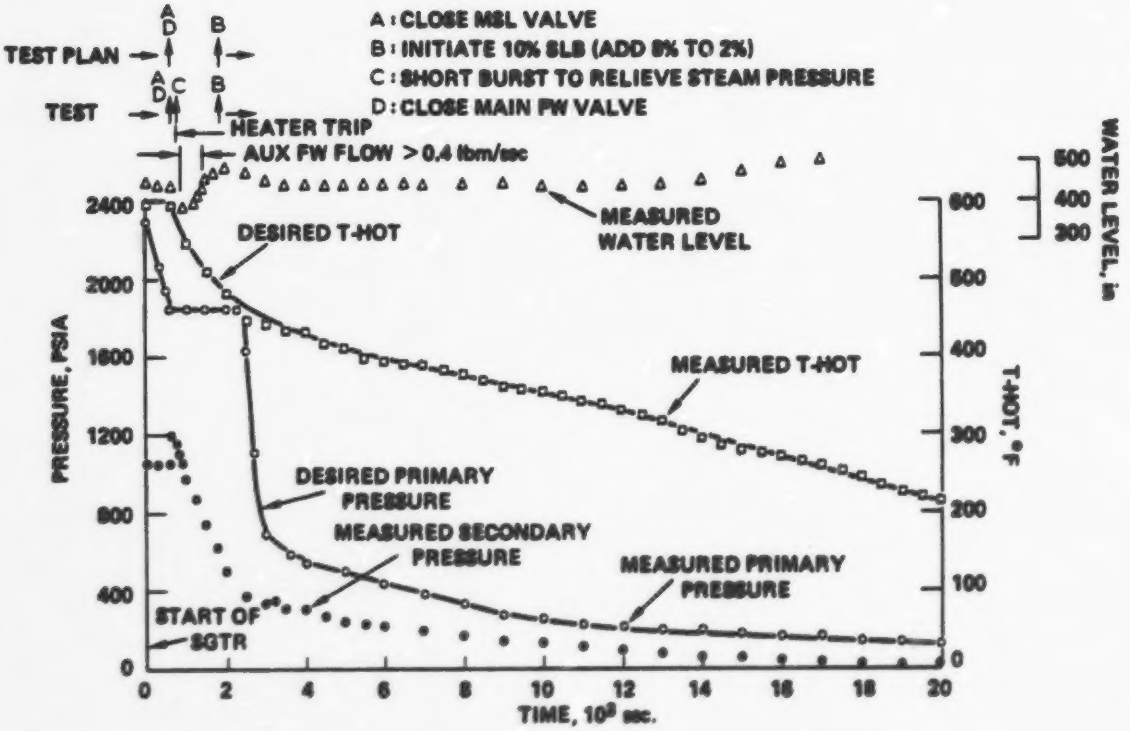

Figure 5-353. Desired and Measured Test Parameters: Test No. 12 (T-2001)

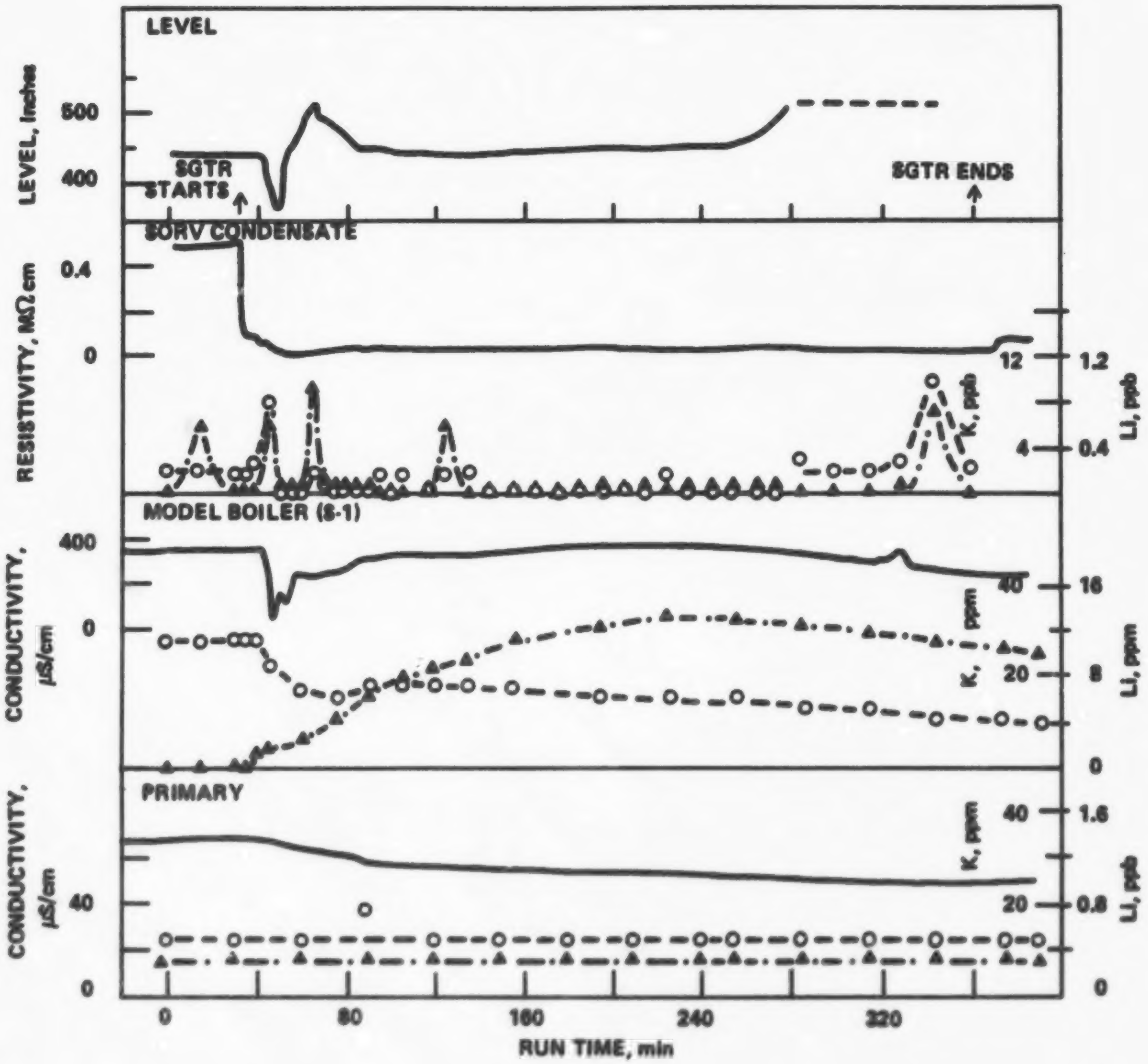

Figure 5-354. Variation in Tracer Concentrations:
Test No. 12 (T-2001)

— · ▲ — · POTASSIUM CONCENTRATION

——— LEVEL, RESISTIVITY OR CONDUCTIVITY

— ○ — LITHIUM CONCENTRATION

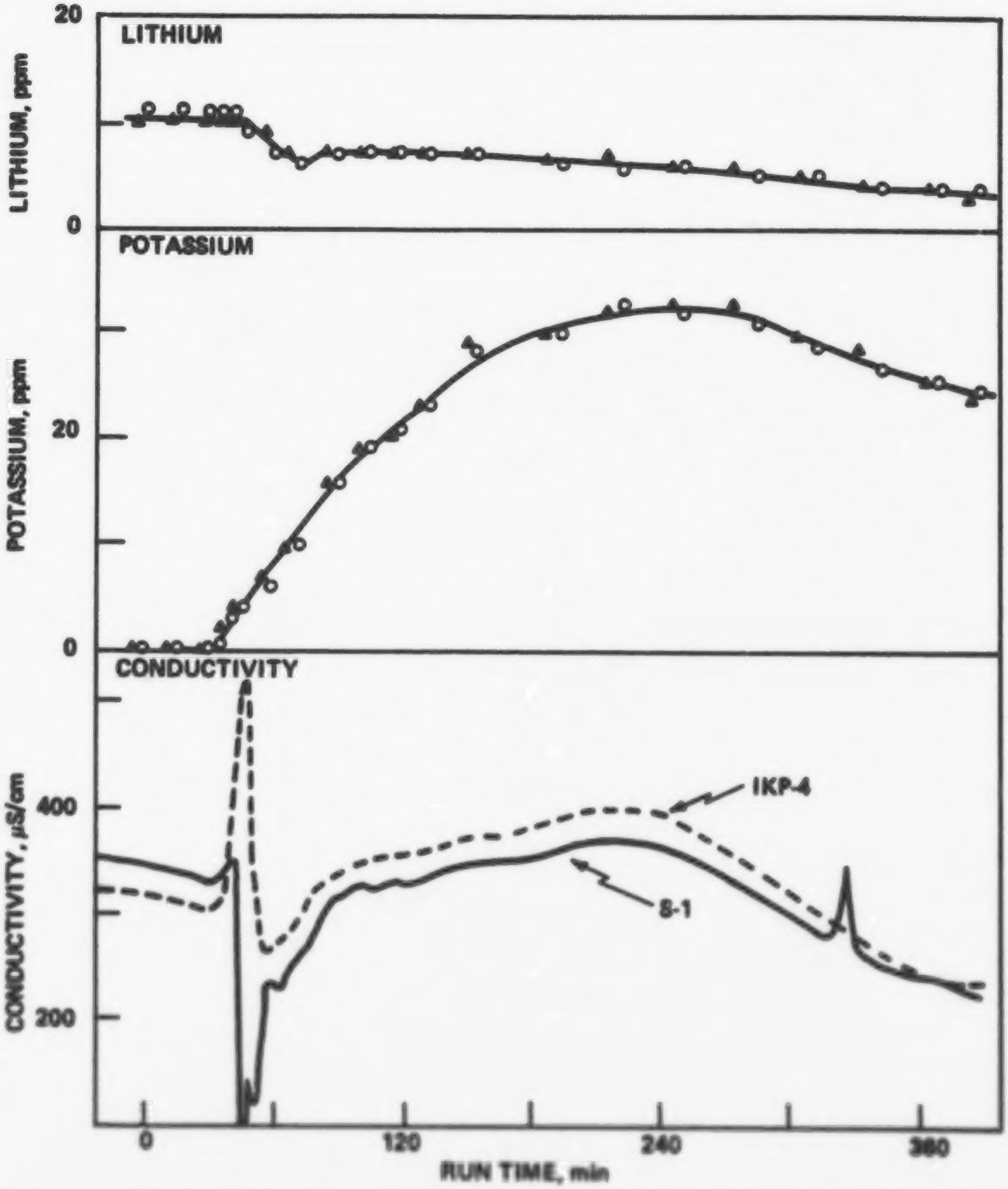

Figure 5-355. Comparison Between S-1 (○) and IKP-4 (▲) Results After Correcting for Sample Line Delays: Test No. 12 (T-2001)

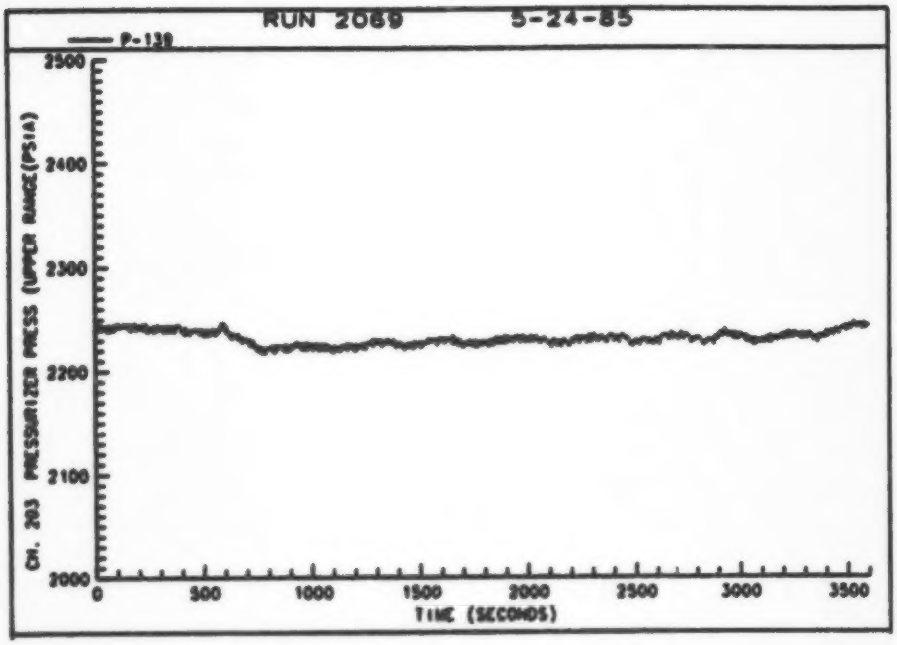

Figure 5-356. Primary System (Pressurizer) Pressure (P-139): Test No. 13 (T-2069)

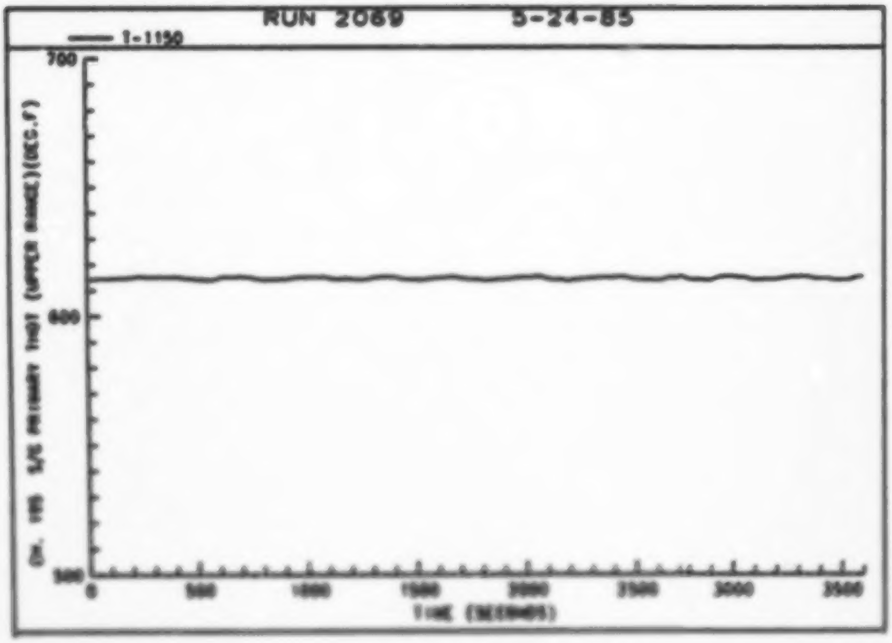

Figure 5-357. Primary Fluid T_{hot} (T-1150):Test No. 13 (T-2069)

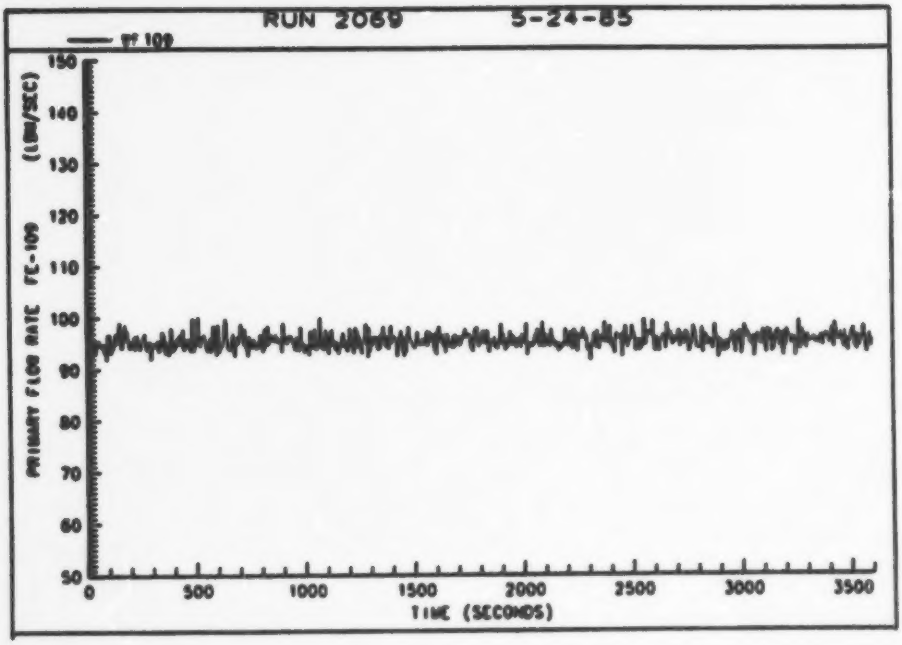

Figure 5-358. Primary Fluid Flow Rate (WF-109): Test No. 13 (T-2069)

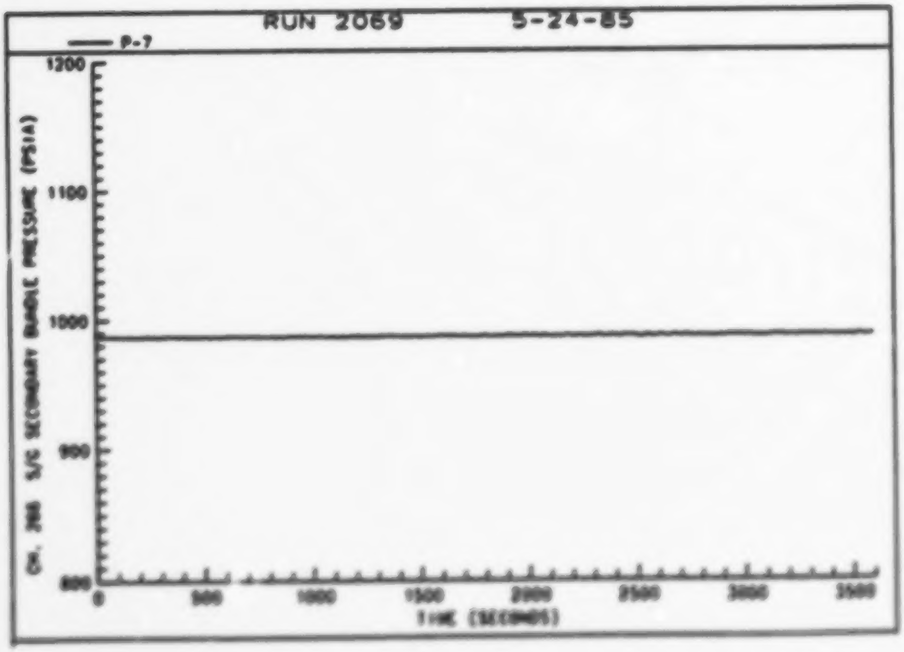

Figure 5-359. Secondary Side Pressure (P-7): Test No. 13 (T-2069)

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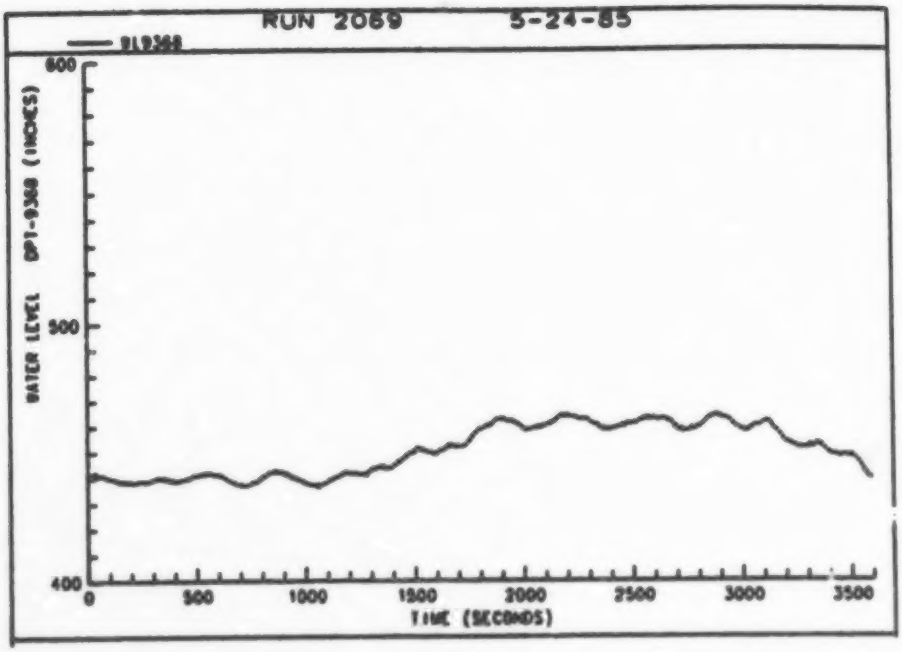

Figure 5-360. Downcomer Water Level - Narrow Range (WL-9368): Test No. 13 (T-2069)

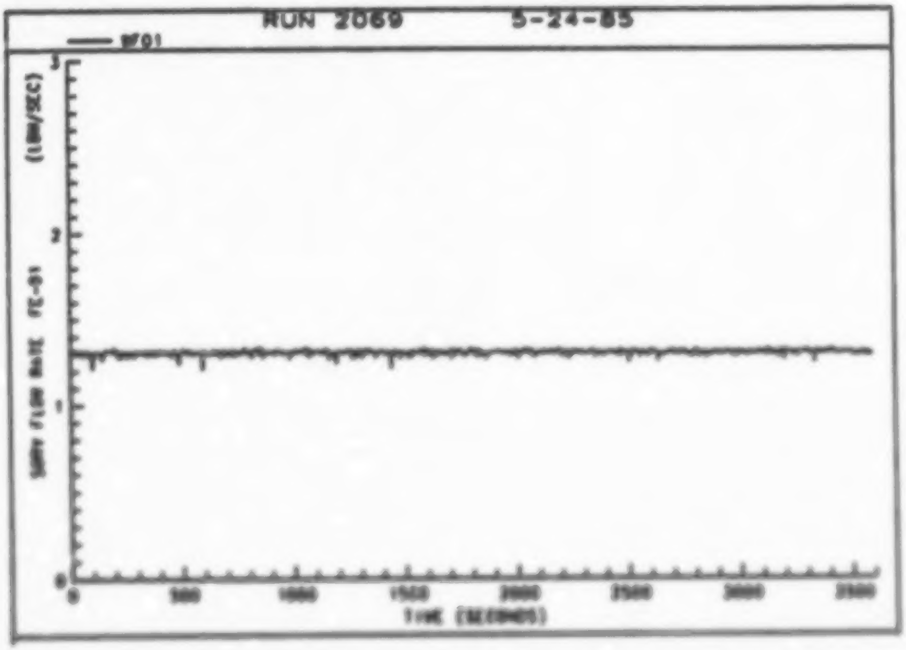

Figure 5-361. SORV Flow Rate (WF-01): Test No. 13 (T-2069)

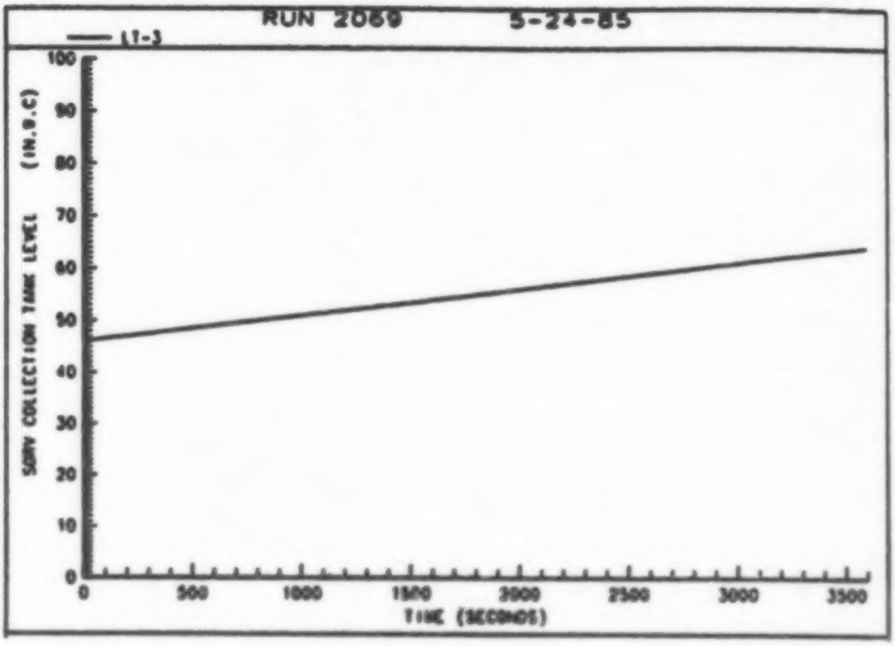

Figure 5-362. SORV Tank Level (LT-3): Test No. 13 (T-2069)

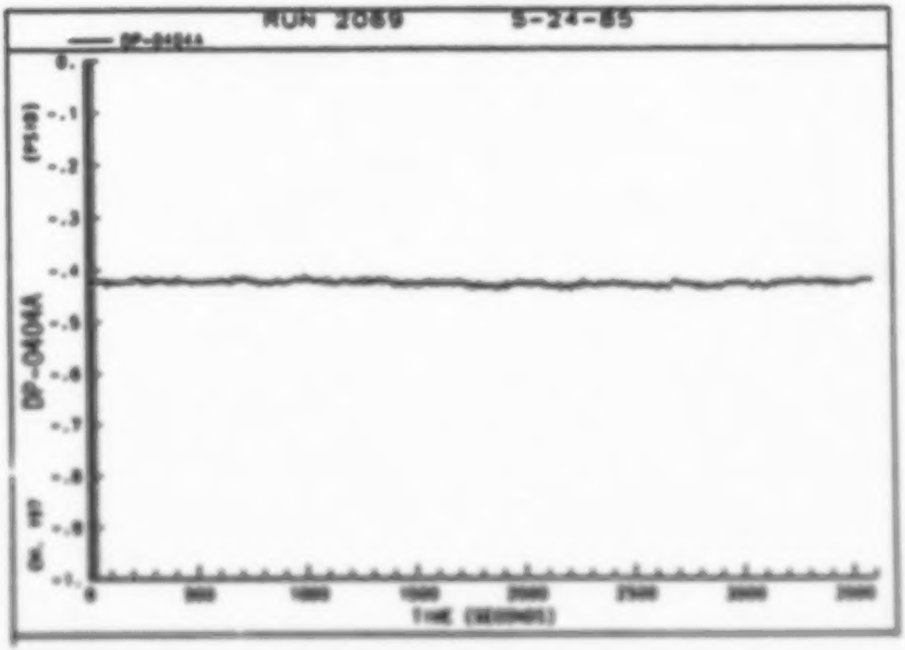

Figure 5-363. Differential Pressure, DP-0404A: Test No. 13 (T-2069)

388

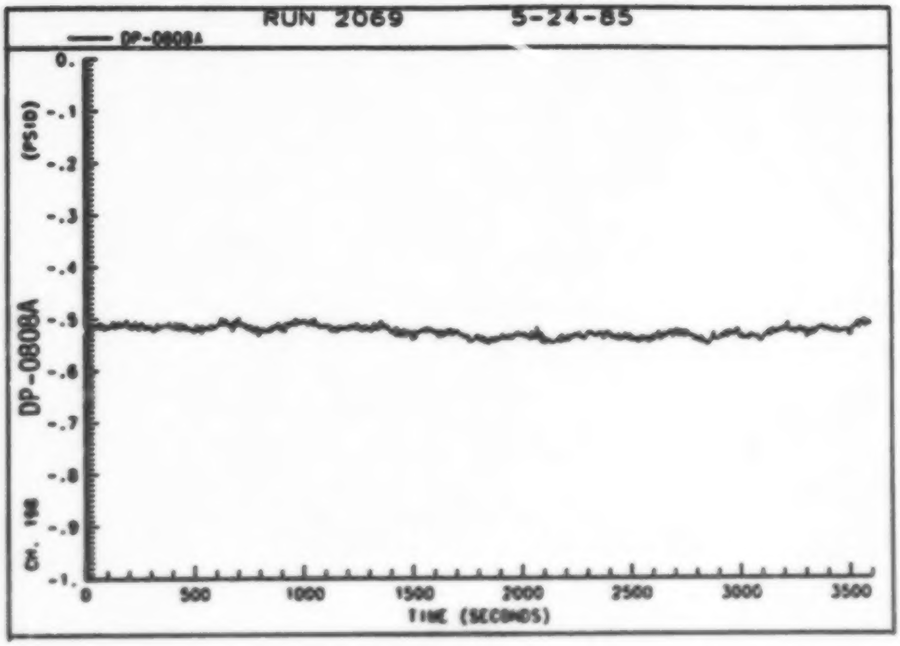

Figure 5-364. Differential Pressure, DP-0808A: Test No. 13 (T-2069)

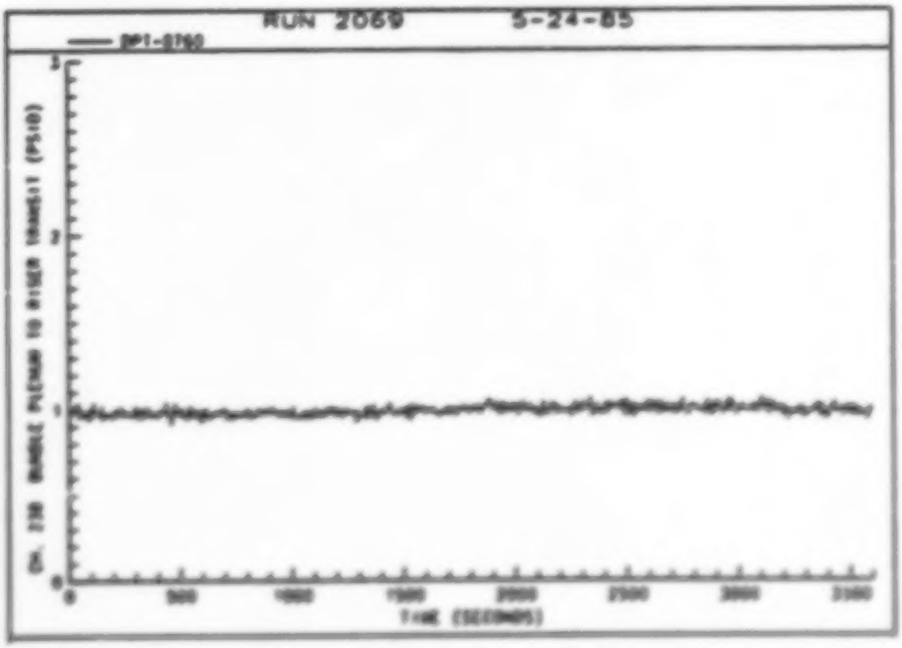

Figure 5-365. Differential Pressure DP-0760: Test No. 13 (T-2069)

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384

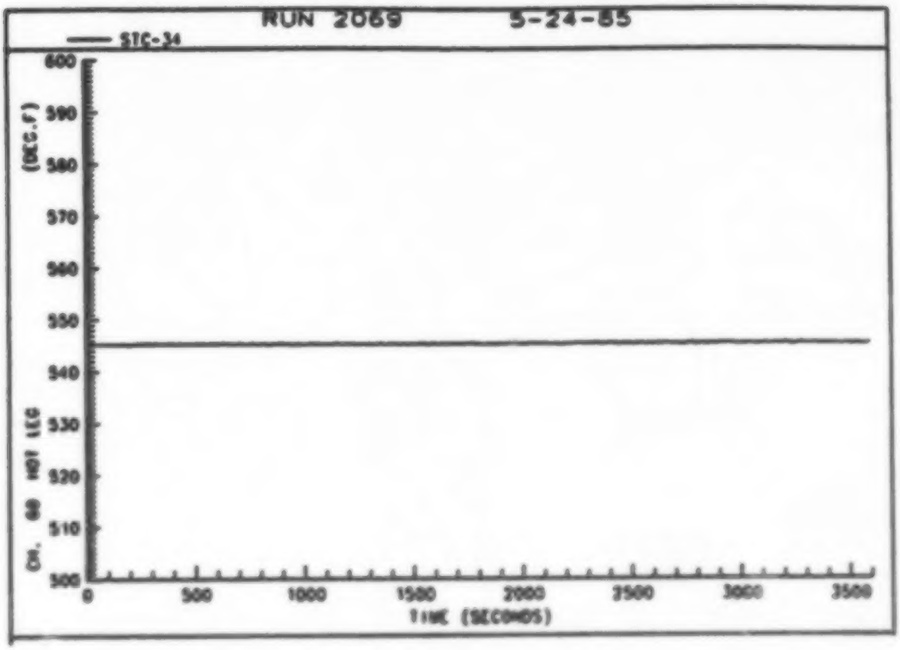

Figure 5-366. Secondary Fluid Temperature (STC-34): Test No. 13 (T-2069)

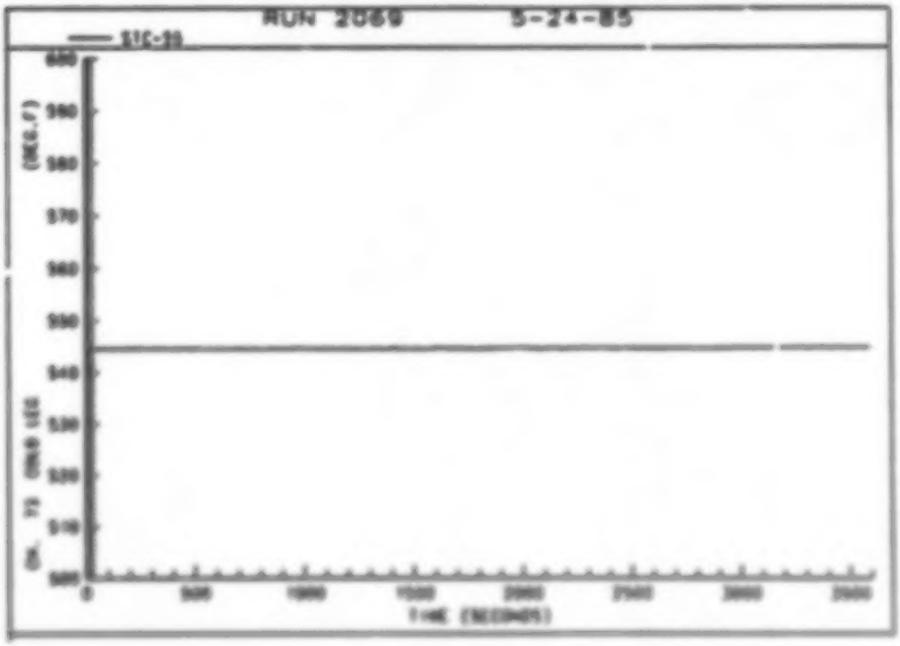

Figure 5-367. Secondary Fluid Temperature (STC-55): Test No. 13 (T-2069)

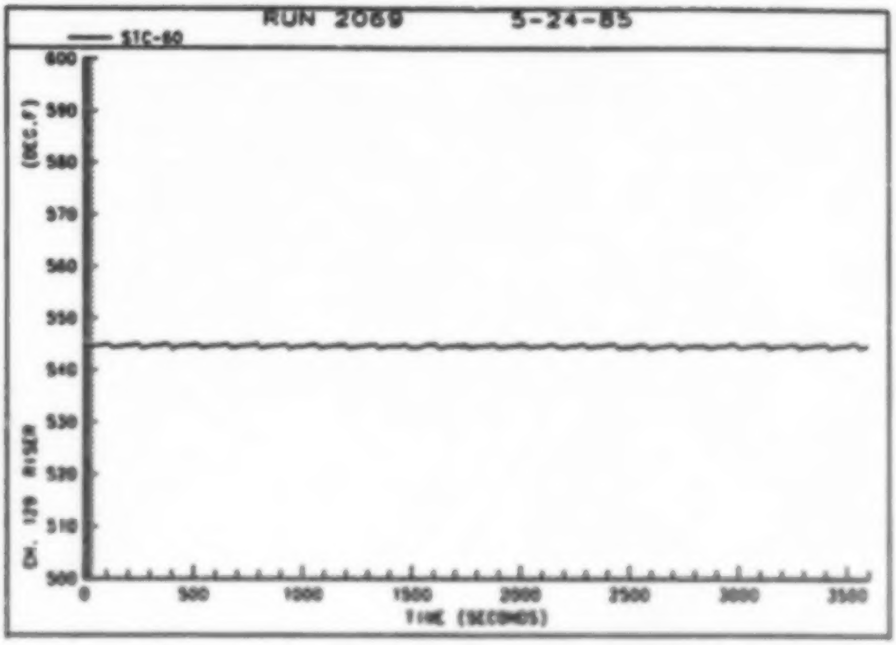

Figure 5-368. Secondary Fluid Temperature (STC-60): Test No. 13 (T-2069)

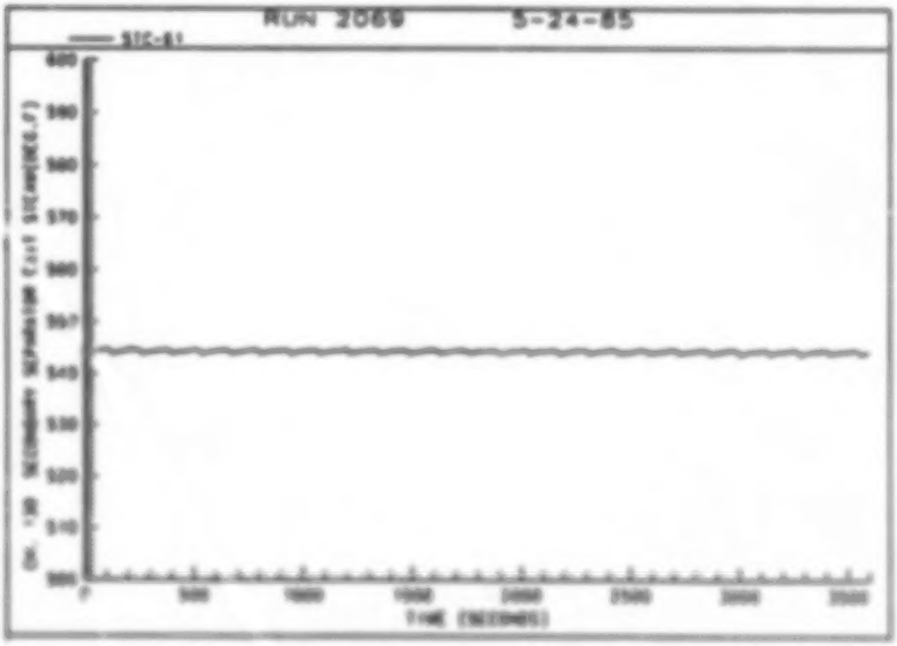

Figure 5-369. Secondary Fluid Temperature (STC-61): Test No. 13 (T-2069)

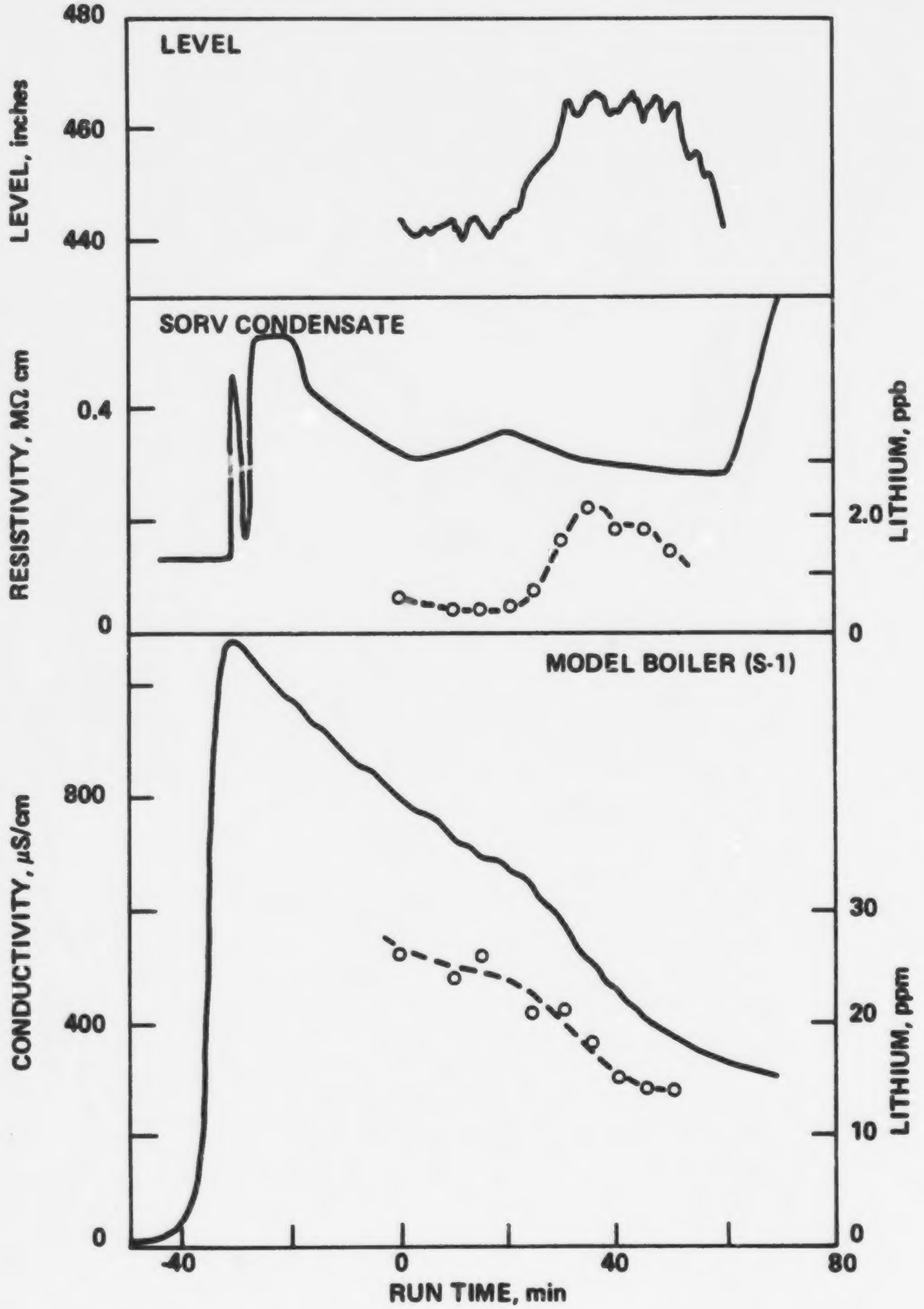

Figure 5-370. Variation in Tracer Concentrations: Test No. 13 (T-2069)

—— LEVEL, RESISTIVITY OR CONDUCTIVITY

—○— LITHIUM CONCENTRATION

392

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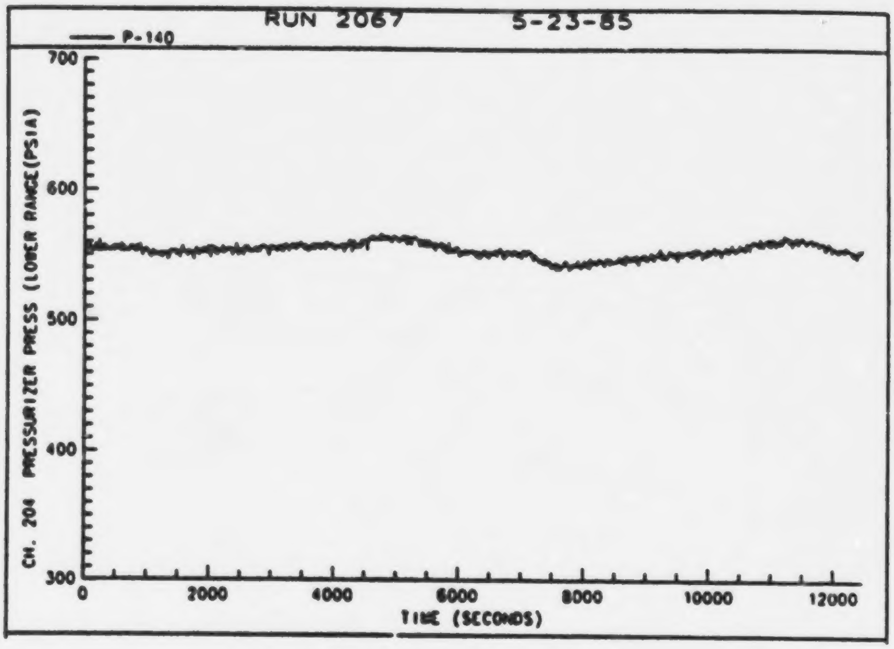

Figure 5-371. Primary System (Pressurizer) Pressure (P-140): Test No. 14 (T-2067)

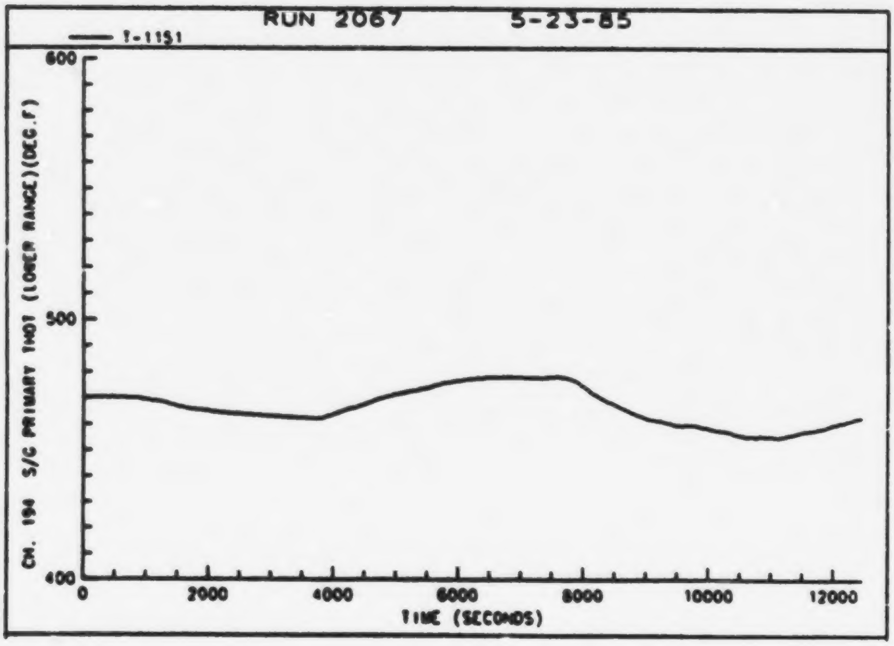

Figure 5-372. Primary Fluid T_{hot} (T-1151): Test No. 14 (T-2067)

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393

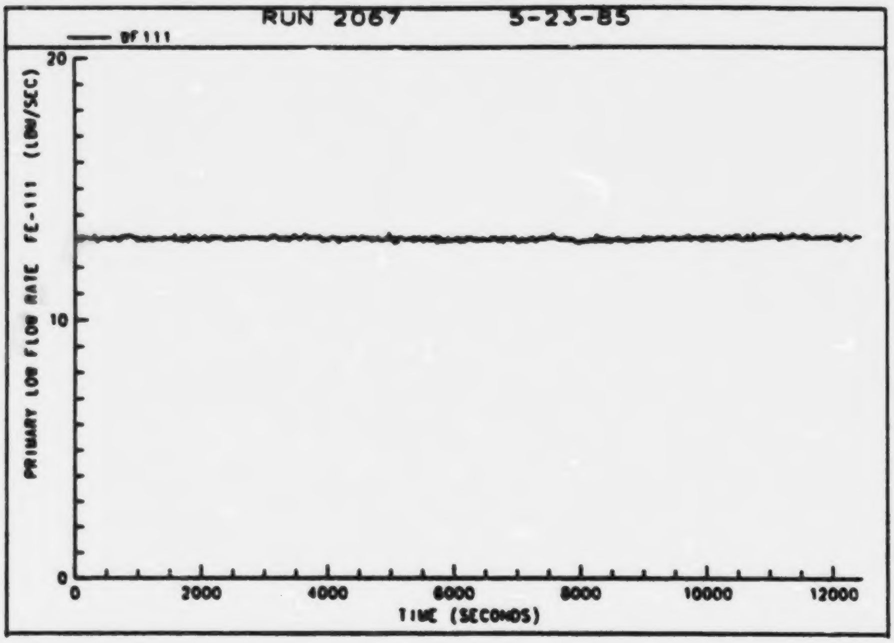

Figure 5-373. Primary Fluid Flow Rate (WF-111): Test No. 14 (T-2067)

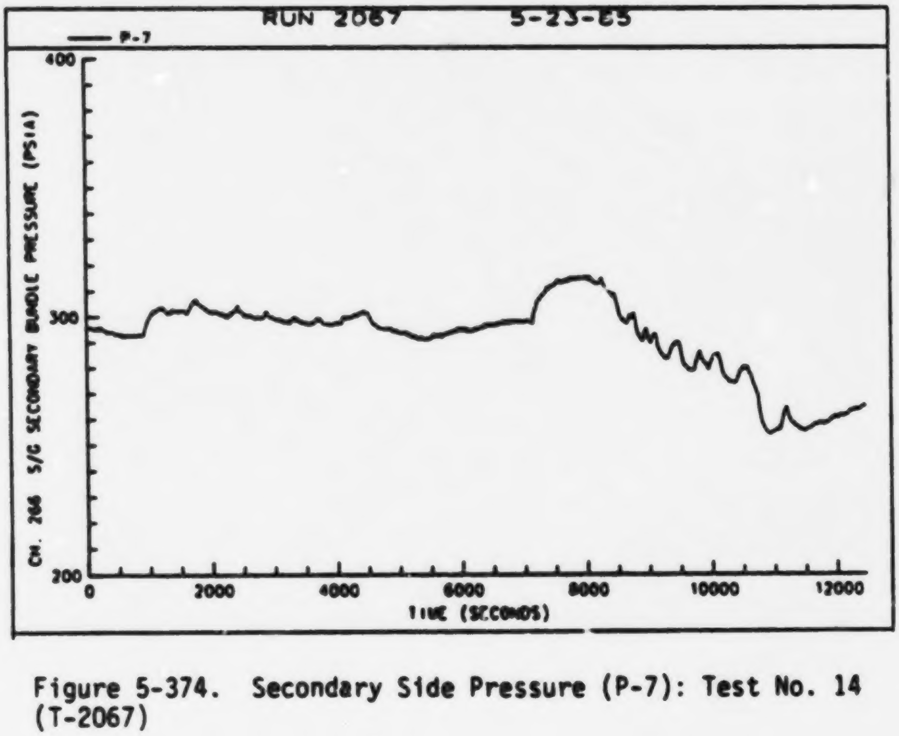

Figure 5-374. Secondary Side Pressure (P-7): Test No. 14 (T-2067)

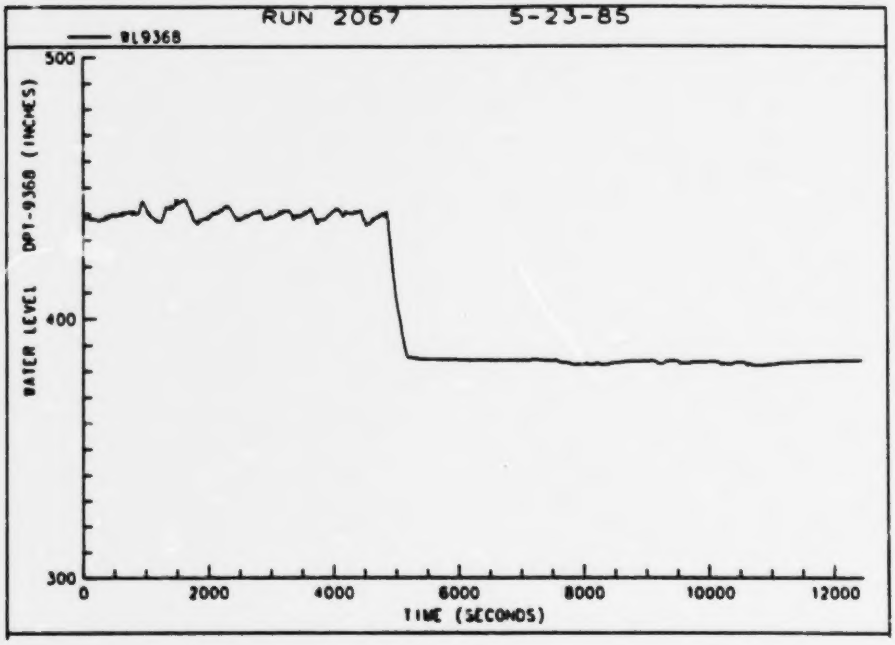

Figure 3-375. Downcomer Water Level - Narrow Range (WL-9368): Test No. 14 (T-2067)

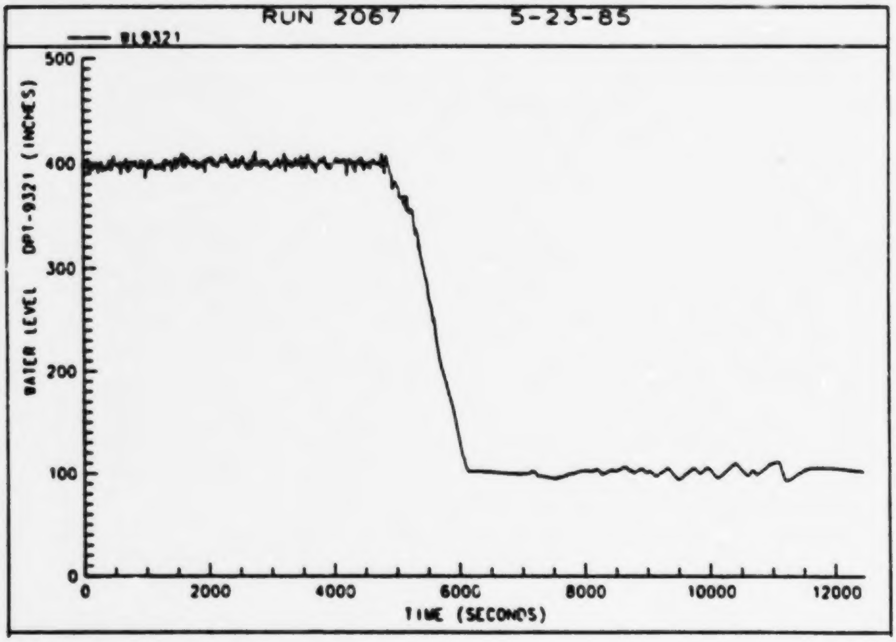

Figure 3-376. Downcomer Water Level - Wide Range (WL-9321): Test No. 14 (T-2067)

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345

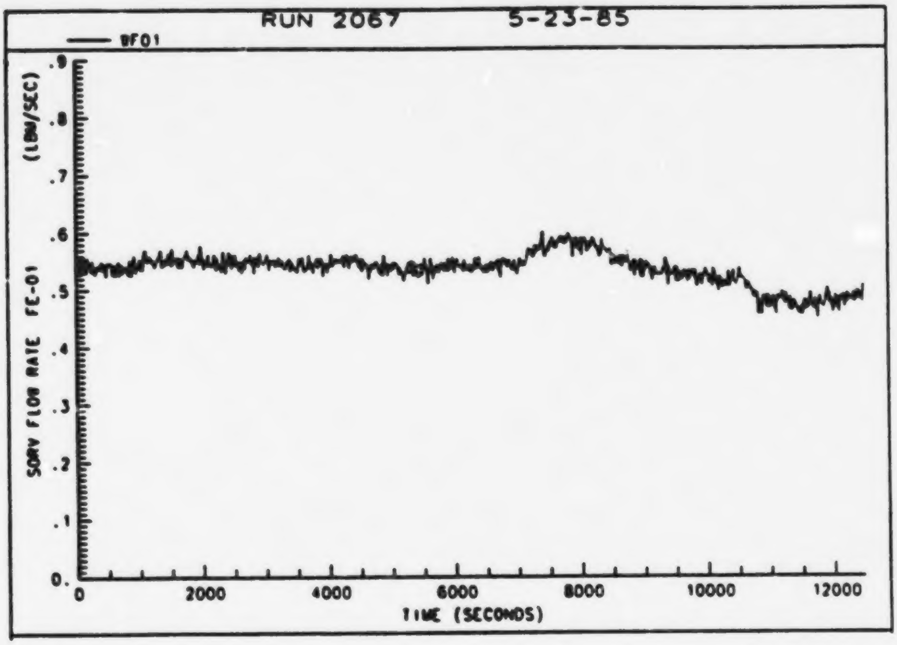

Figure 5-377. SORV Flow Rate (WF-01): Test No. 14 (T-2067)

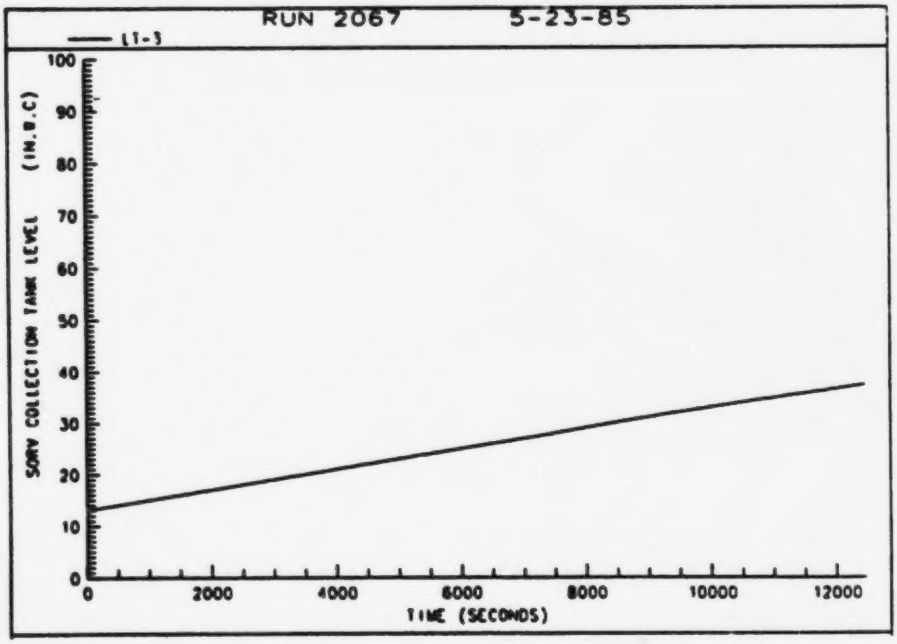

Figure 5-378. SORV Tank Level (LT-3): Test No. 14 (T-2067)

396

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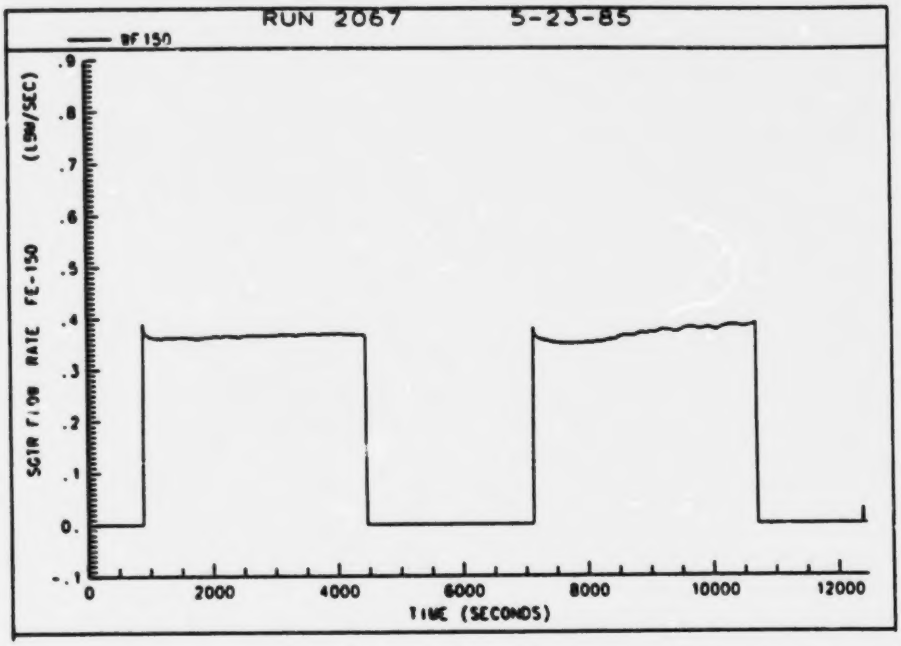

Figure 5-379. SGTR Flow Rate (WF-150): Test No. 14 (T-2067)

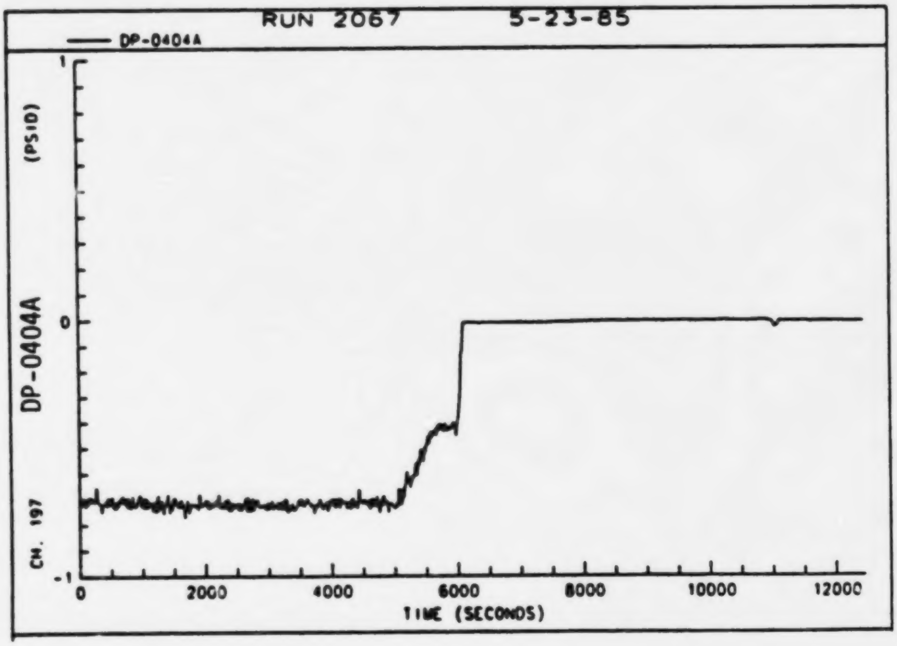

Figure 380. Differential Pressure, DP-0404A:
Test No. 14 (T-2067)

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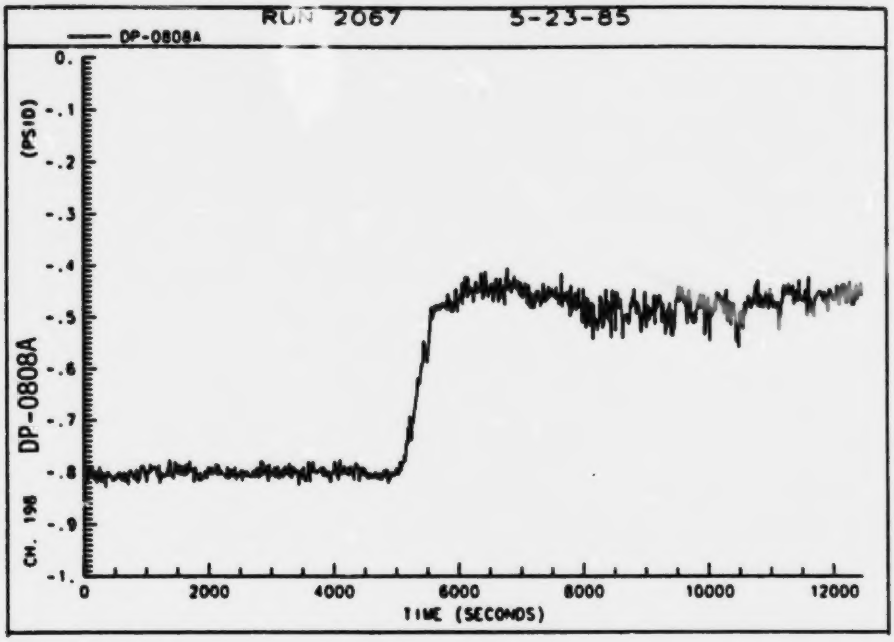

Figure 5-381. Differential Pressure, DP-0808A: Test No. 14 (T-2067)

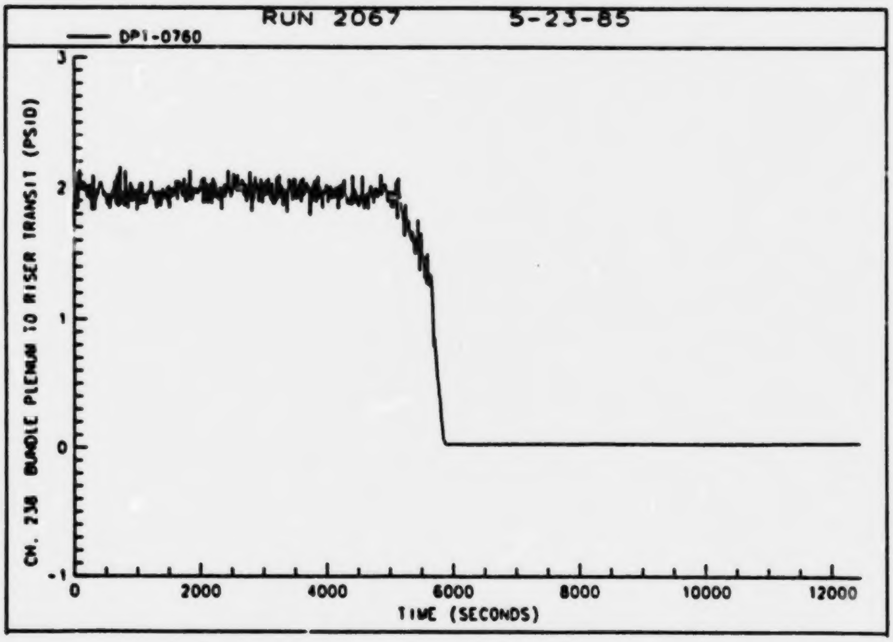

Figure 5-382. Differential Pressure, DP-0760: Test No. 14 (T-2067)

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398

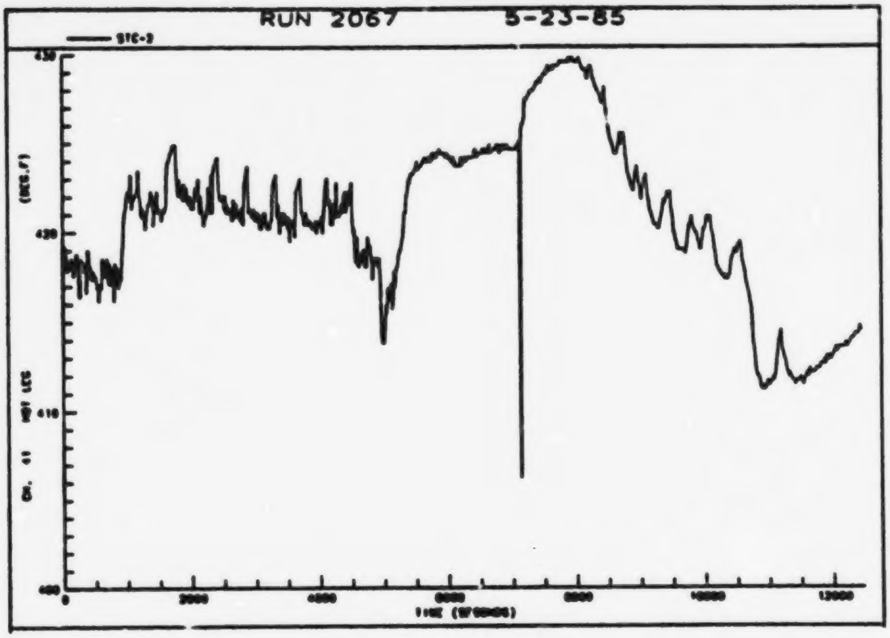

Figure 5-383. Secondary Fluid Temperature (STC-2): Test No. 14 (T-2067)

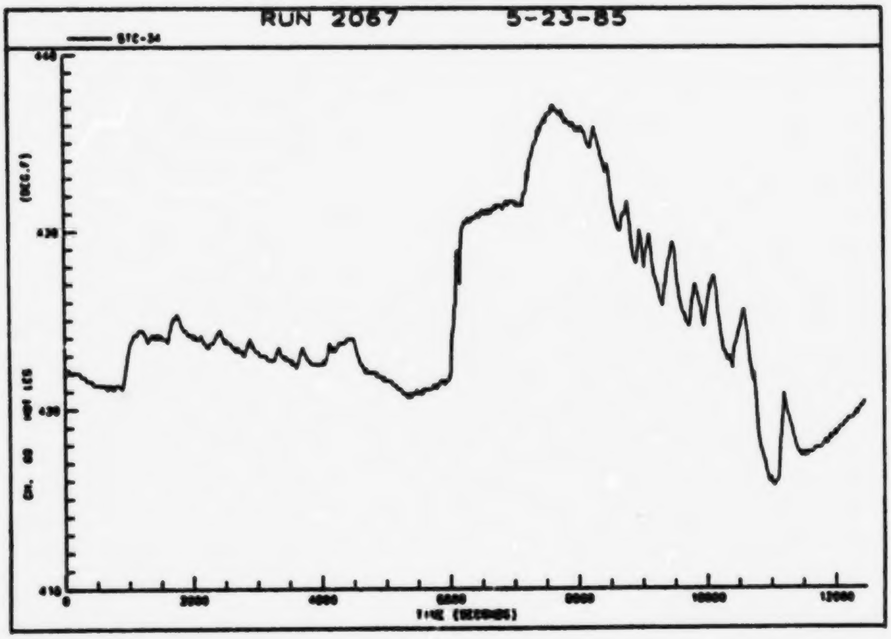

Figure 5-384. Secondary Fluid Temperature (STC-34): Test No. 14 (T-2067)

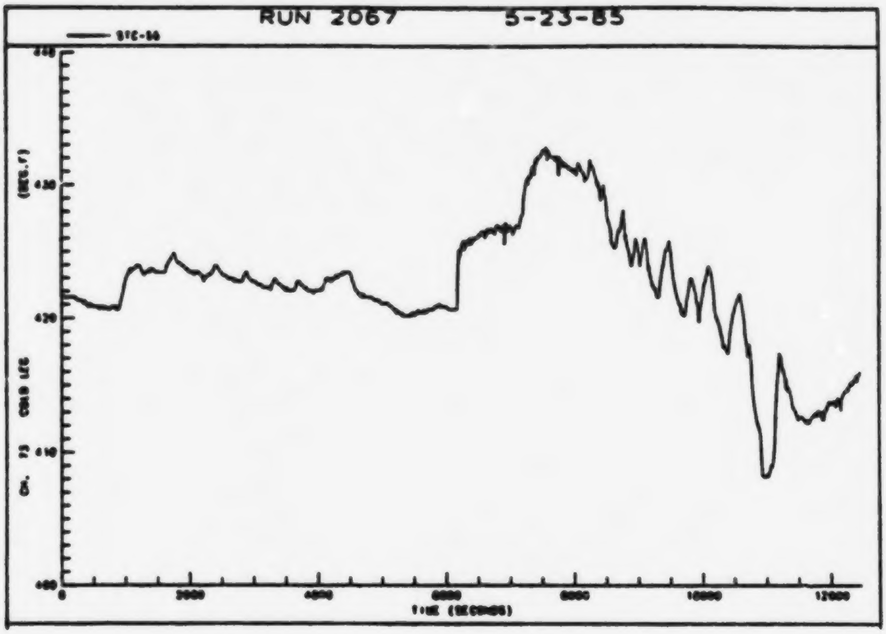

Figure 5-385. Secondary Fluid Temperature (STC-55): Test No. 14 (T-2067)

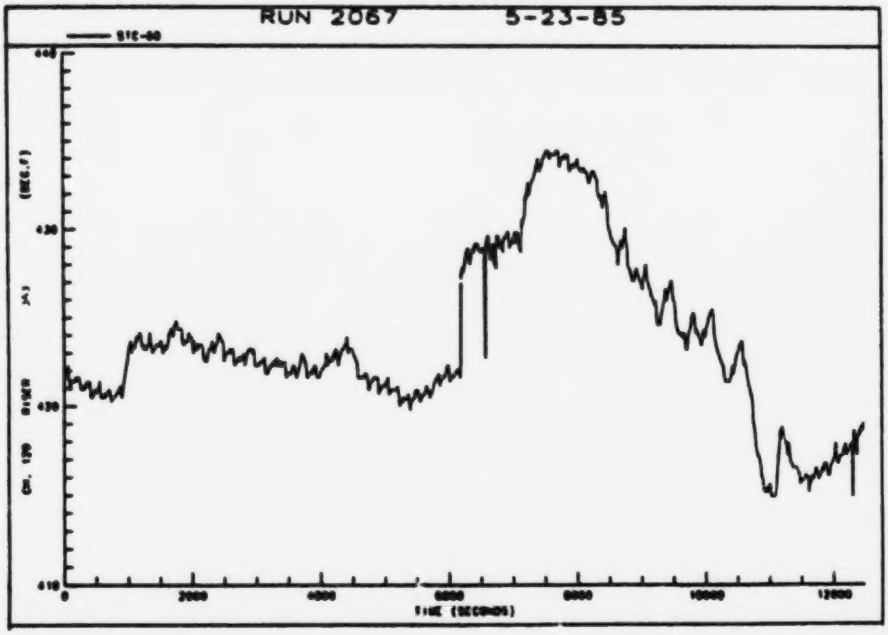

Figure 5-386. Secondary Fluid Temperature (STC-60): Test No. 14 (T-2067)

400

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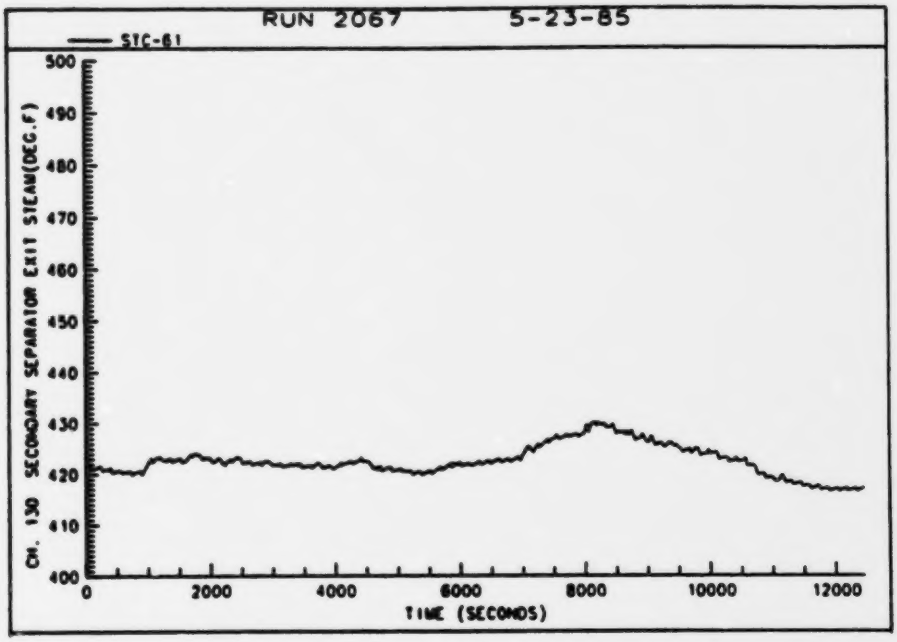

Figure 5-387. Secondary Fluid Temperature (STC-61): Test No. 14 (T-2067)

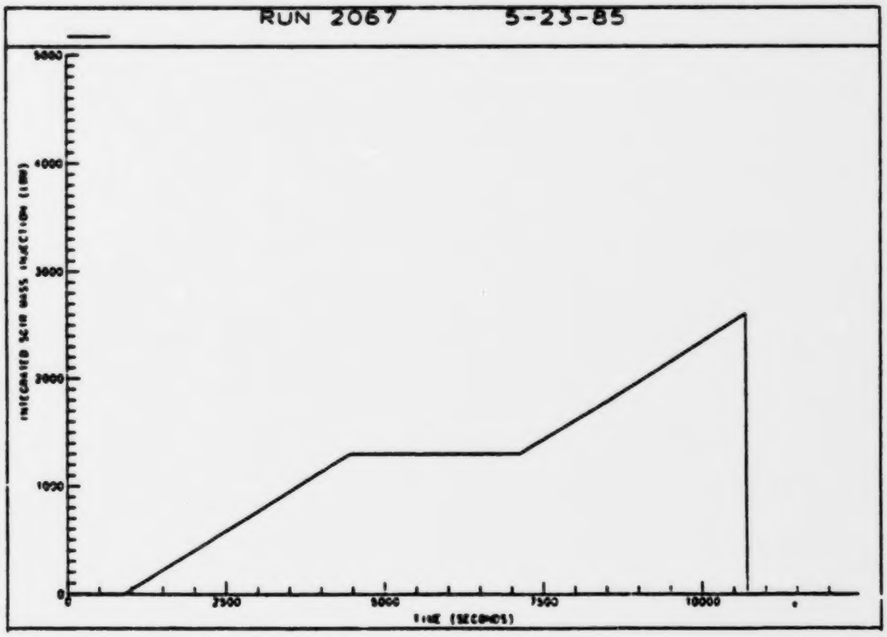

Figure 5-388. Integrated SGTR Flow: Test No. 14 (T-2067)

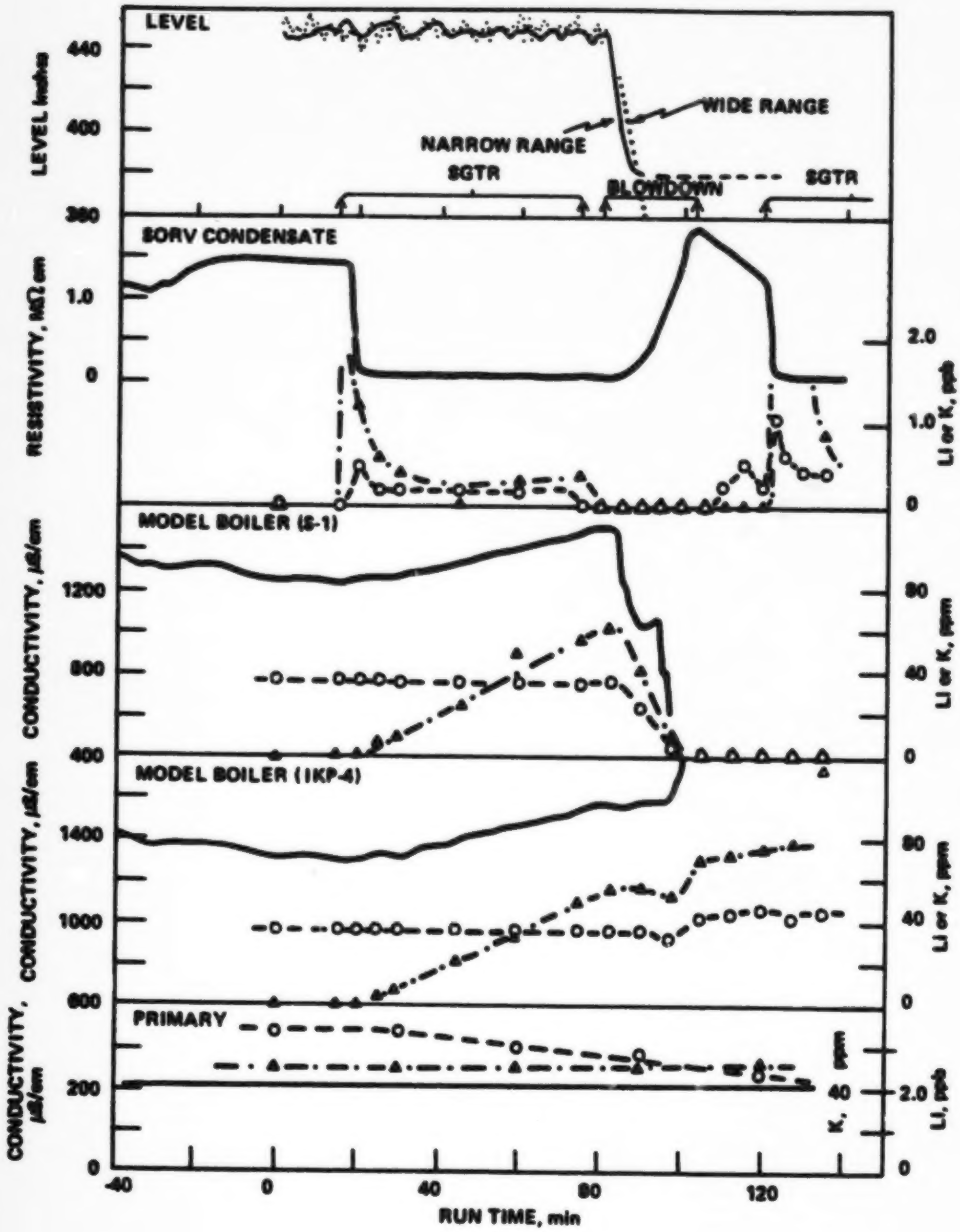

Figure 5-389. Variation in Tracer Concentrations: SGTR at Normal Water Level, Test No. 14 (T-2067)

—·▲—· POTASSIUM CONCENTRATION
—— LEVEL, RESISTIVITY OR CONDUCTIVITY
— ○ — LITHIUM CONCENTRATION

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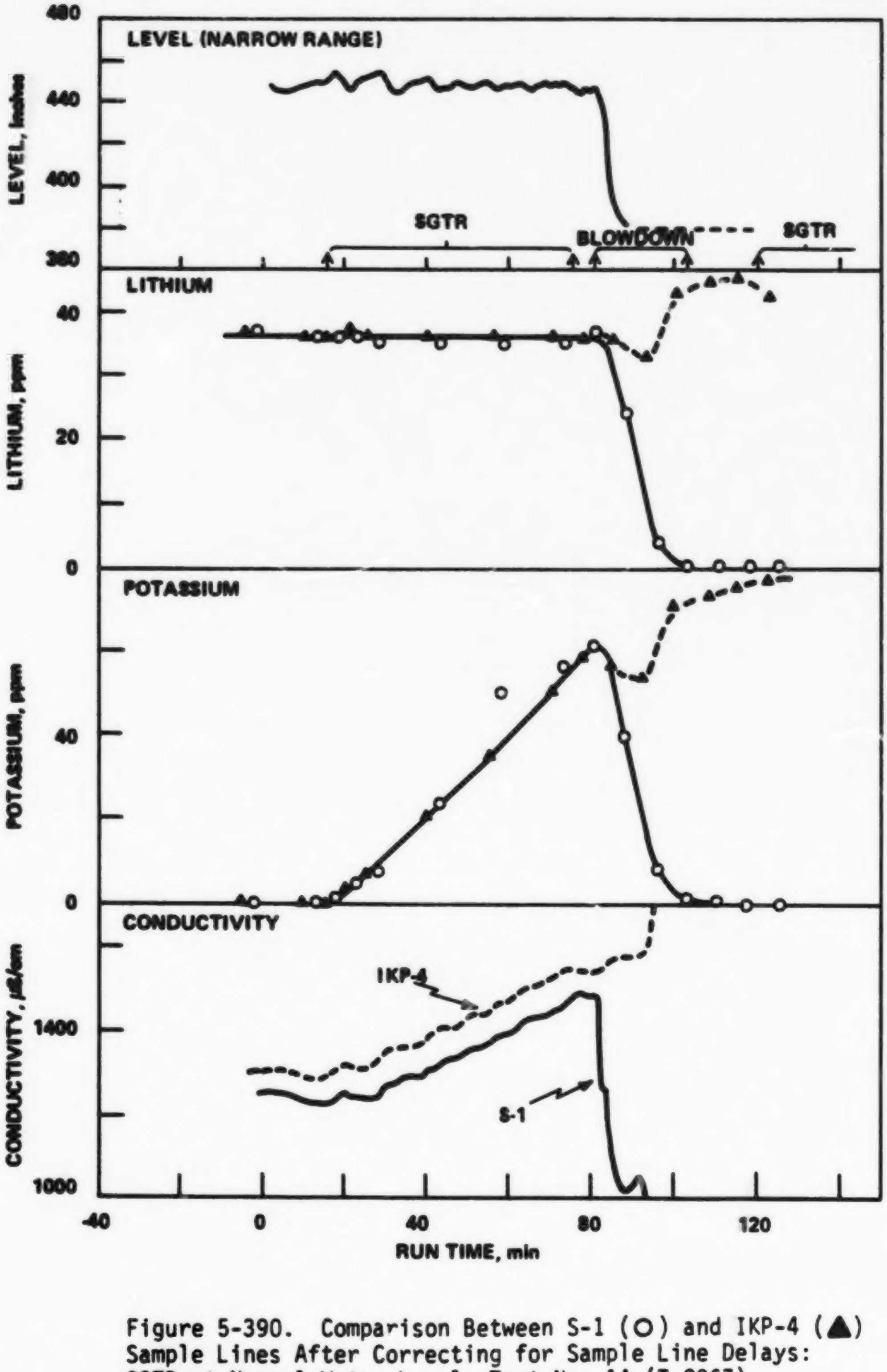

Figure 5-390. Comparison Between S-1 (○) and IKP-4 (▲) Sample Lines After Correcting for Sample Line Delays: SGTR at Normal Water Level, Test No. 14 (T-2067)

403

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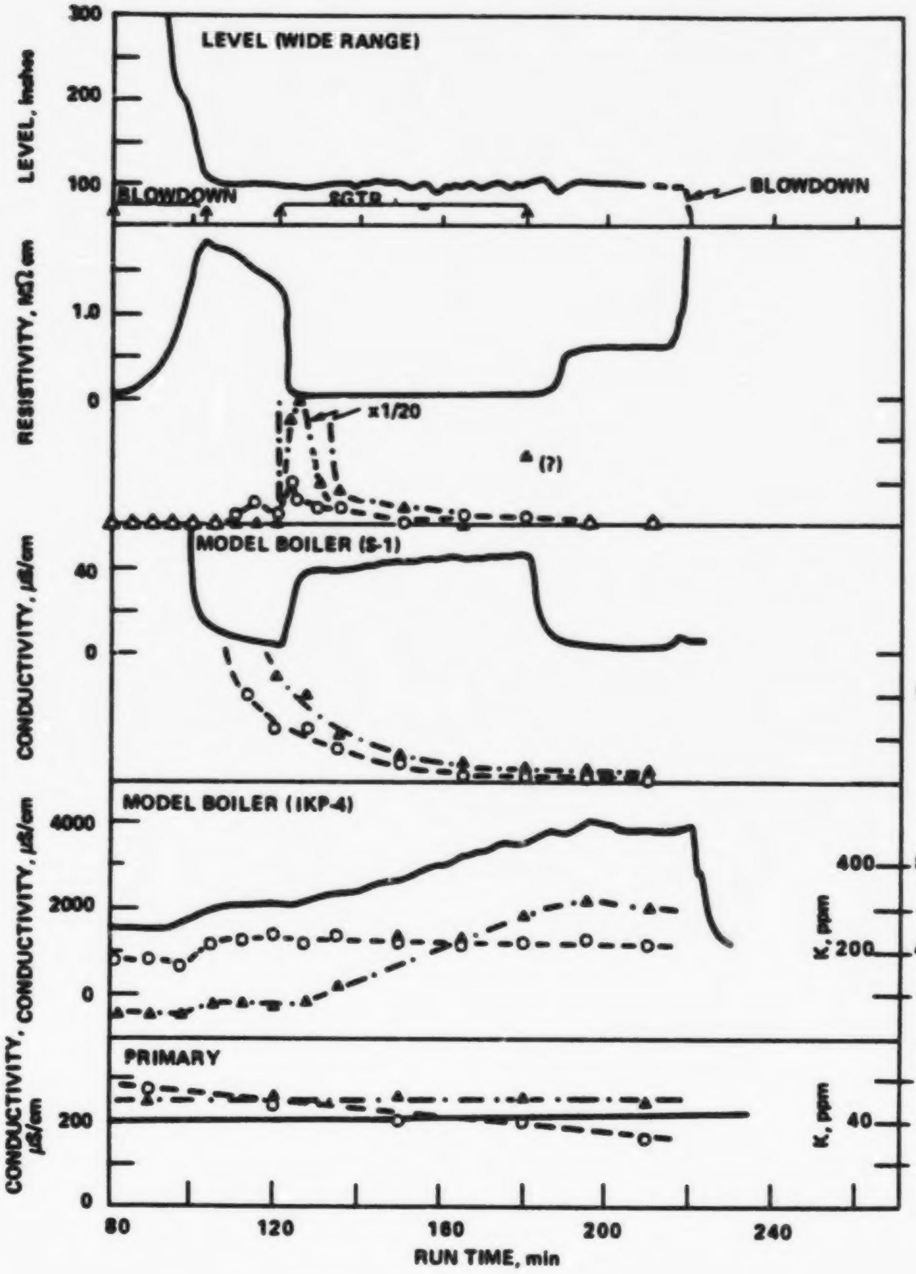

Figure 5-391. Variation in Tracer Concentrations: SGTR at 102.5 in., Test No. 14 (T-2067)

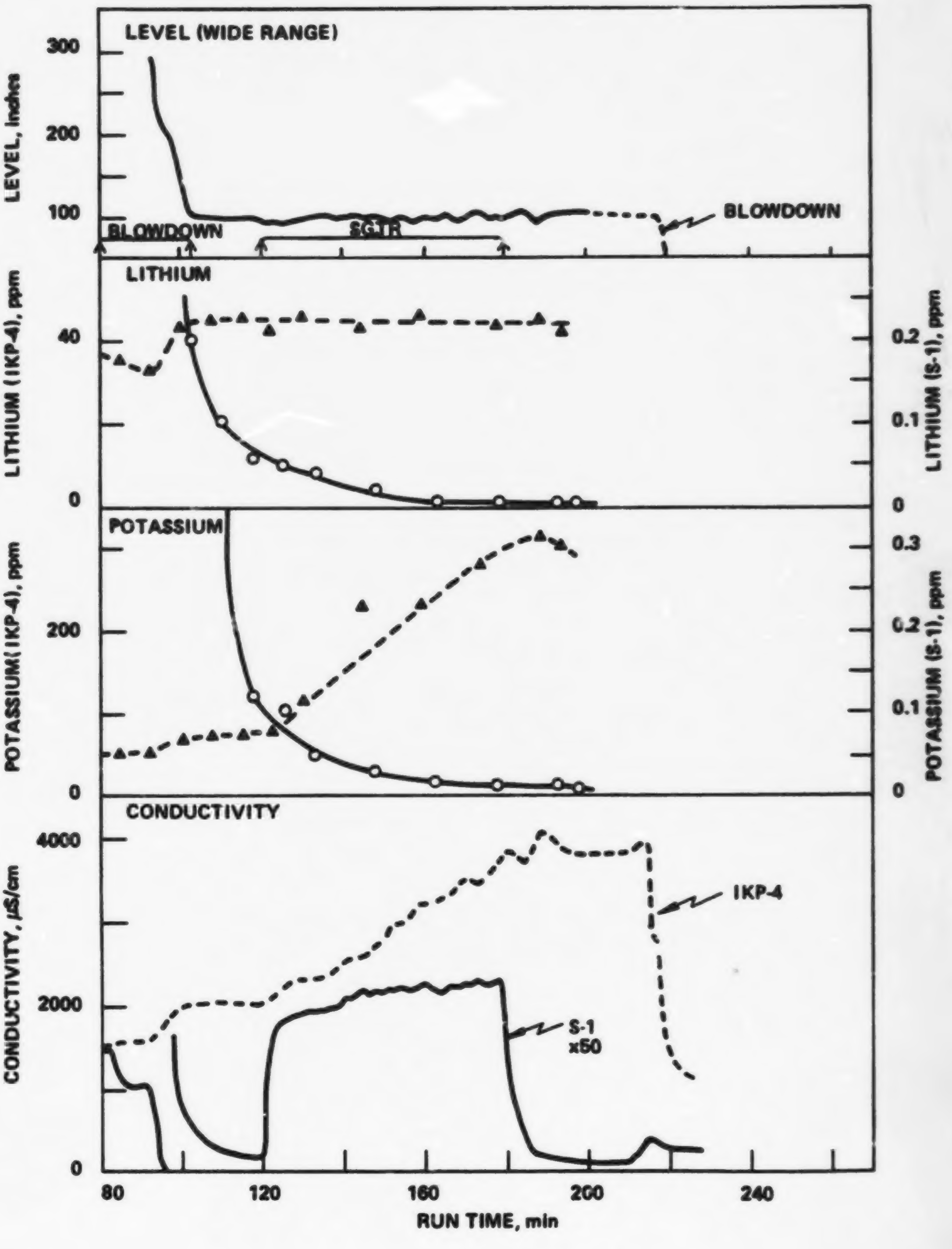

Figure 5-392. Comparison Between S-1 (○) and IKP-4 (▲) Results: SGTR at 102.5 in., Test No. 14 (T-2067)

405

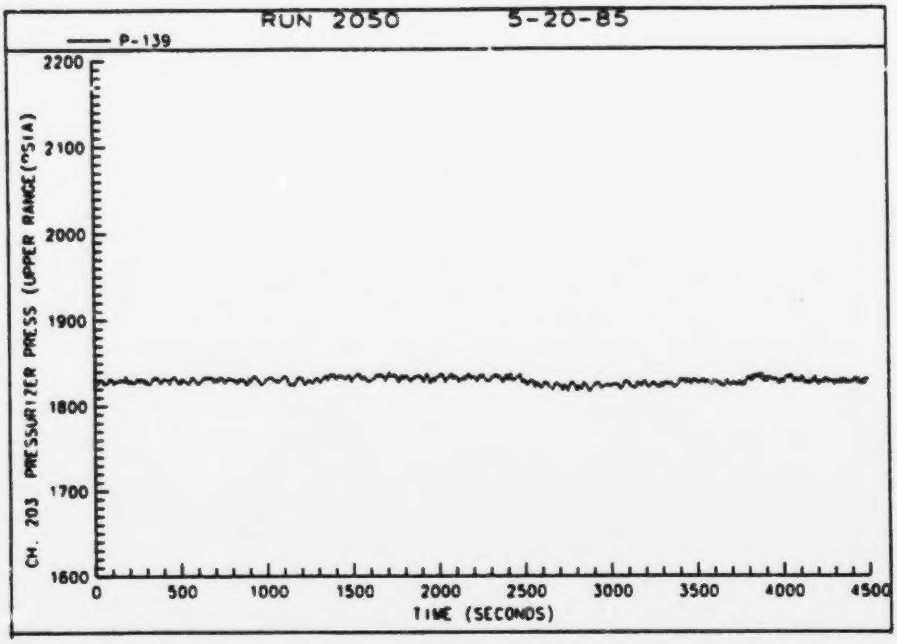

Figure 5-393. Primary System (Pressurizer) Pressure (P-139): Test No. 15 (T-2050)

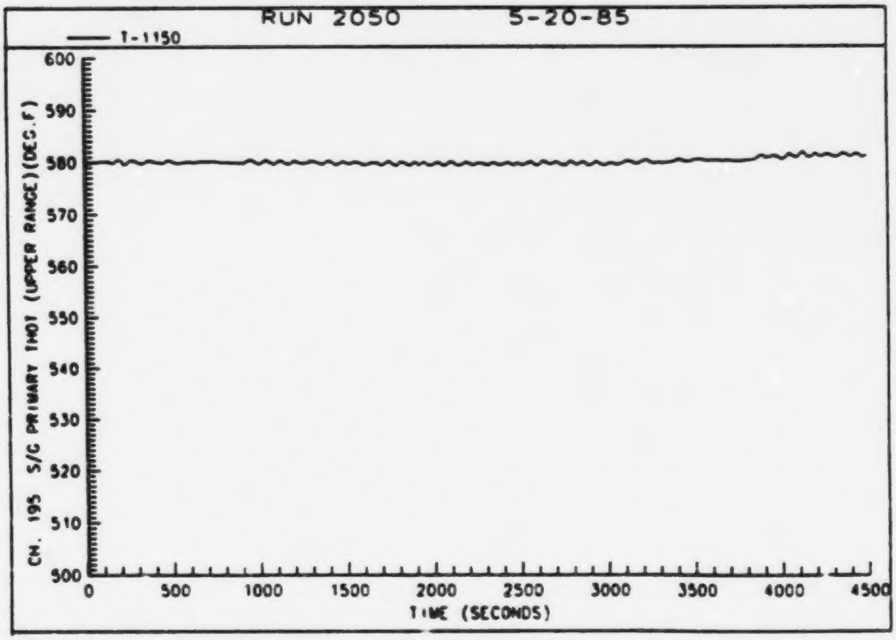

Figure 5-394. Primary Fluid T_{hot} (T-1150): Test No. 15 (T-2050)

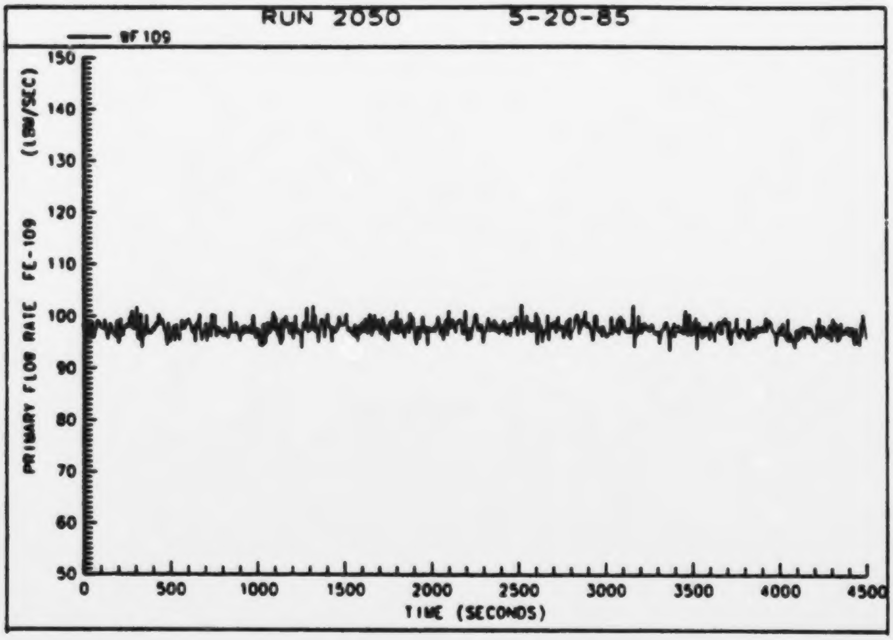

Figure 5-395. Primary Fluid Flow Rate (WF-109): Test No. 15 (T-2050)

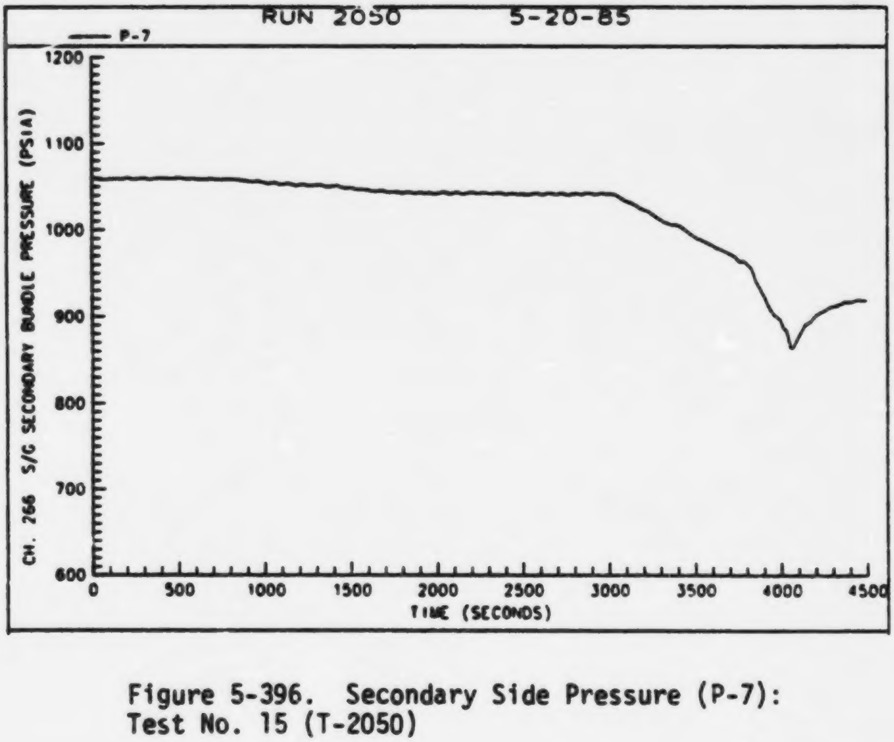

Figure 5-396. Secondary Side Pressure (P-7): Test No. 15 (T-2050)

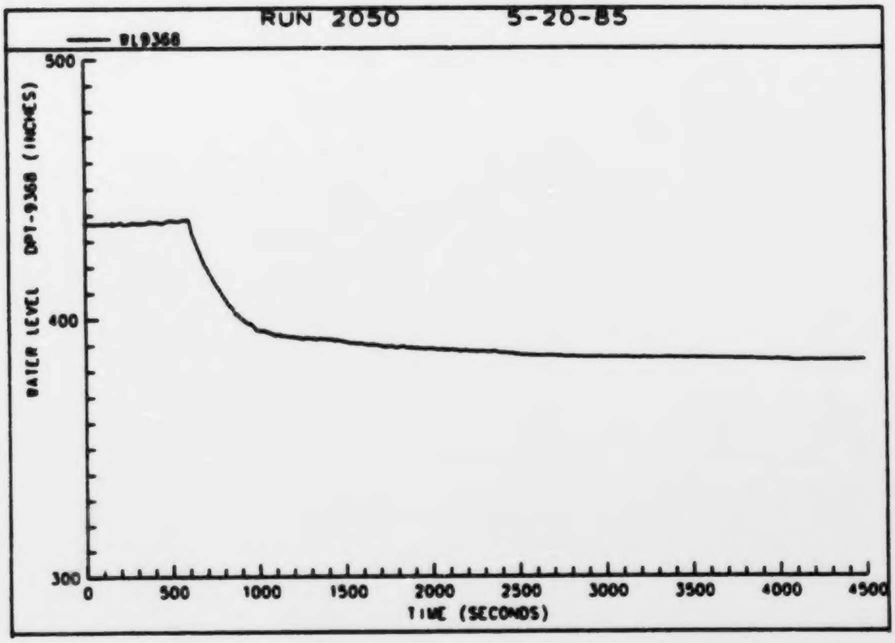

Figure 5-397. Downcomer Water Level - Narrow Range (WL-9368): Test No. 15 (T-2050)

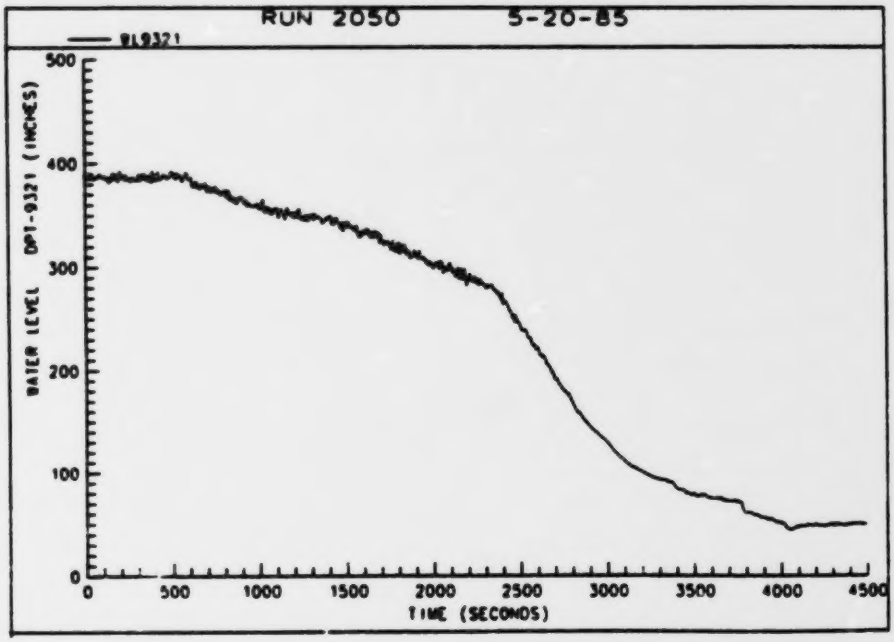

Figure 5-398. Downcomer Water Level - Wide Range (WL-9321): Test No. 15 (T-2050)

408

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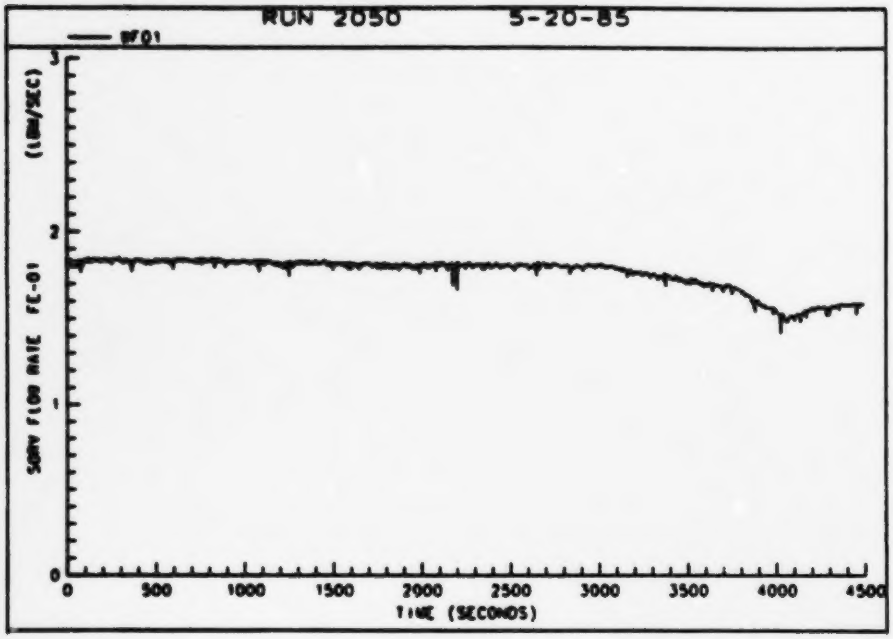

Figure 5-399. SORV Flow Rate (WF-01): Test No. 15 (T-2050)

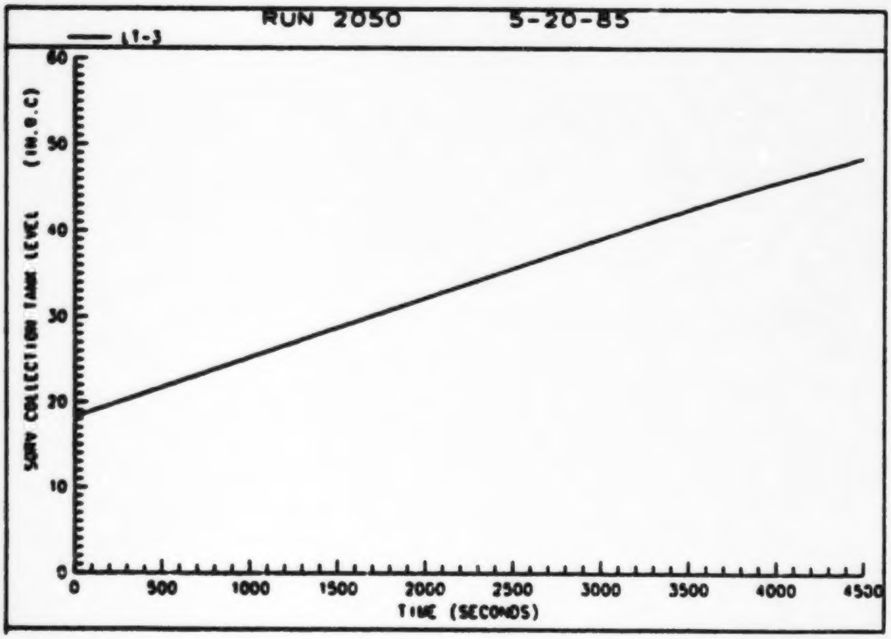

Figure 5-400. SORV Tank Level (LT-3): Test No. 15 (T-2050)

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409

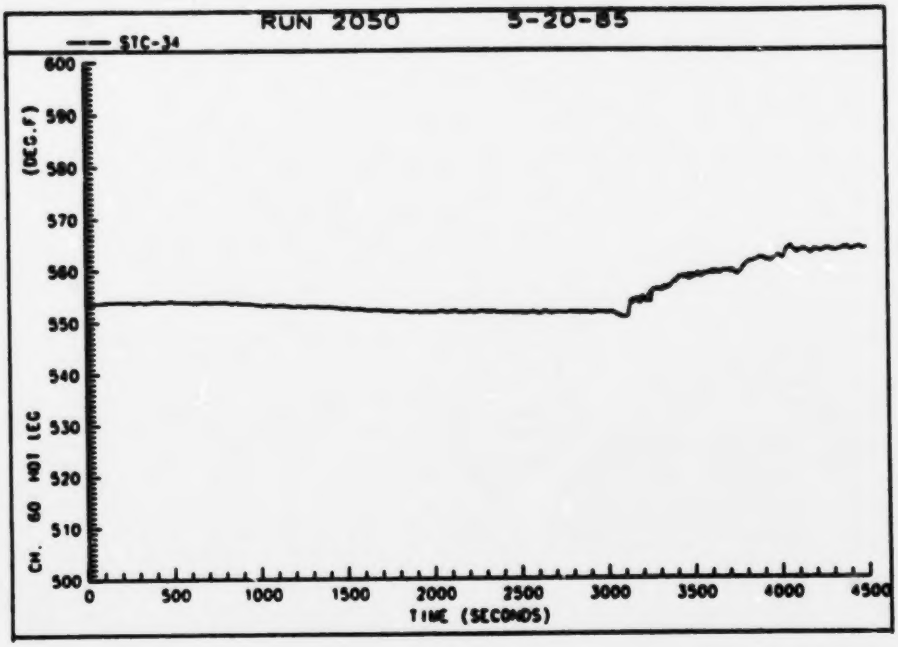

Figure 5-401. Secondary Fluid Temperature (STC-34): Test No. 15 (T-2050)

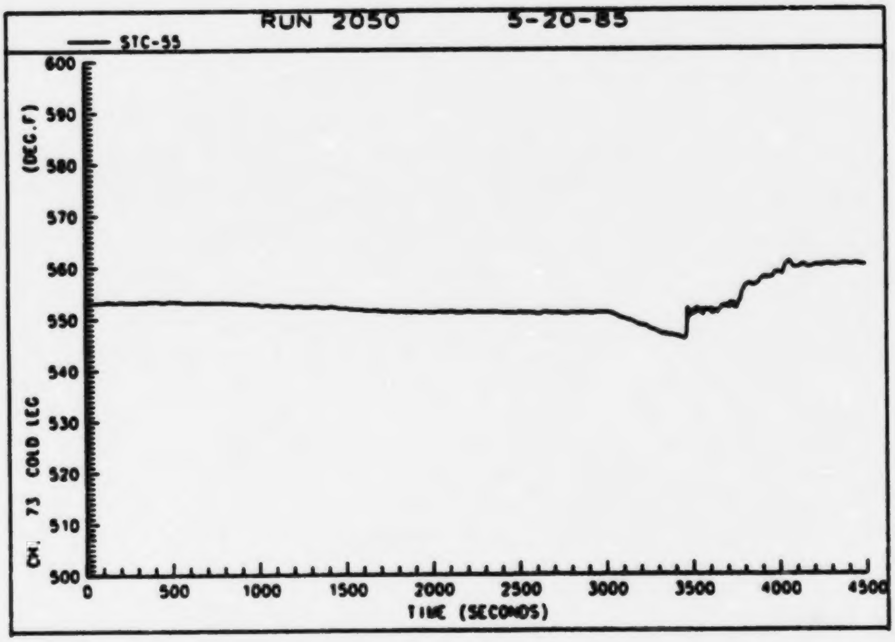

Figure 5-402. Secondary Fluid Temperature (STC-55): Test No. 15 (T-2050)

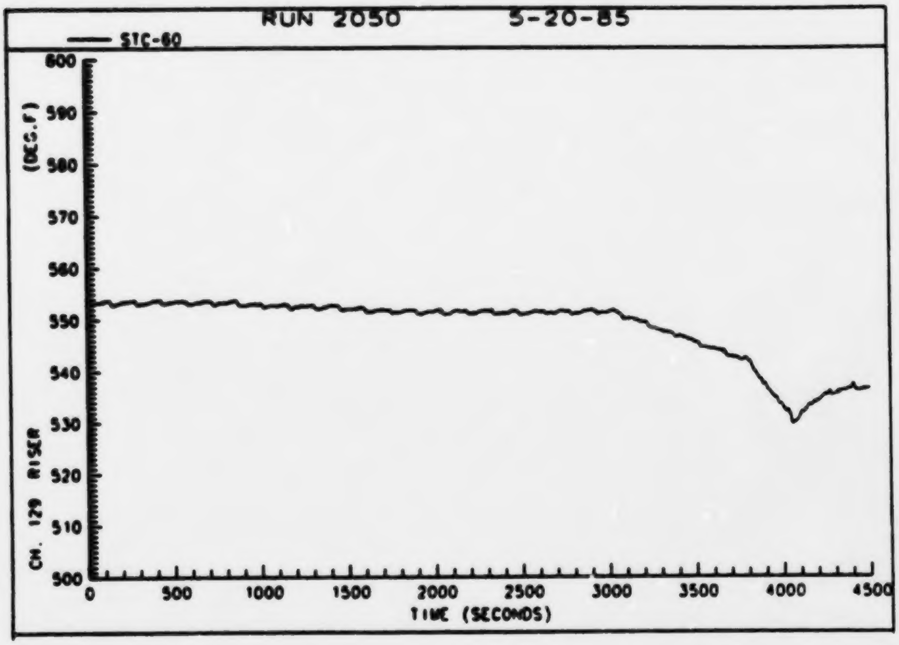

Figure 5-403. Secondary Fluid Temperature (STC-60): Test No. 15 (T-2050)

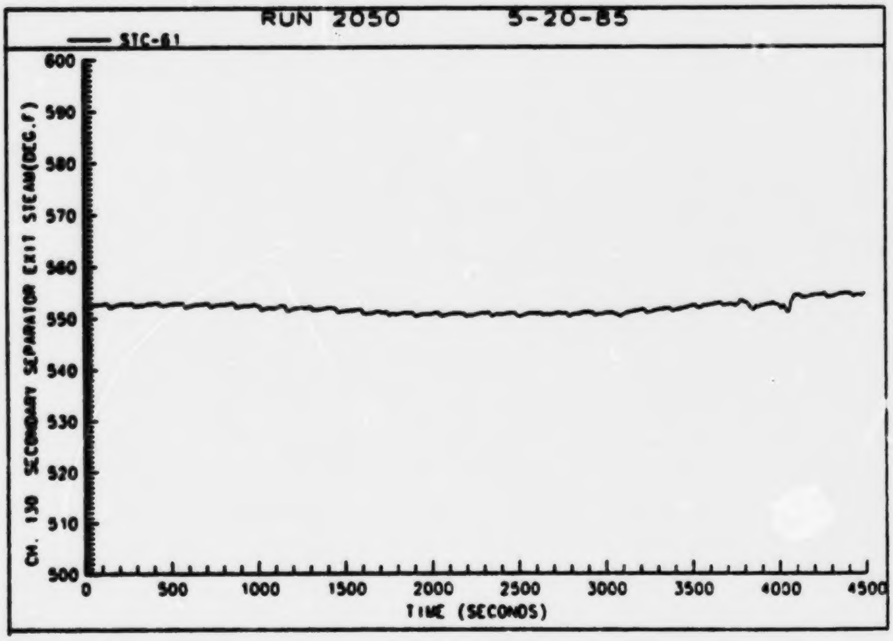

Figure 5-404. Secondary Fluid Temperature (STC-61): Test No. 15 (T-2050)

411

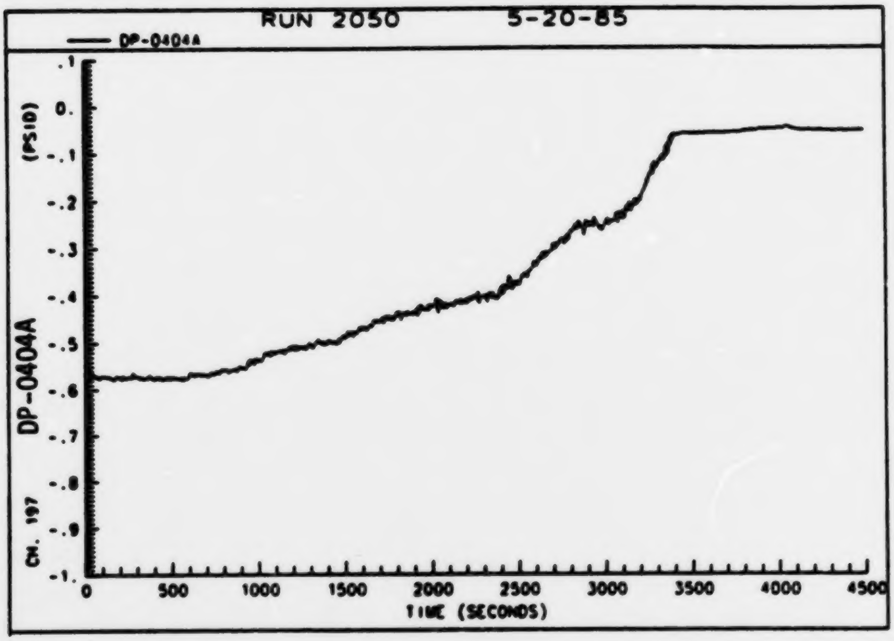

Figure 5-405. Differential Pressure, DP-0404A: Test No. 15 (T-2050)

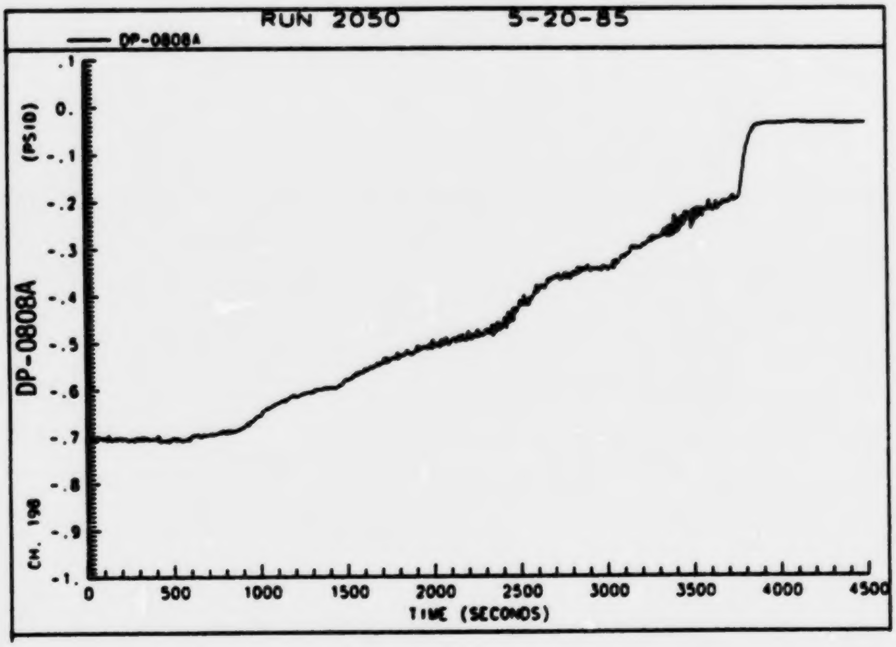

Figure 5-406. Differential Pressure, DP-0808A: Test No. 15 (T-2050)

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412

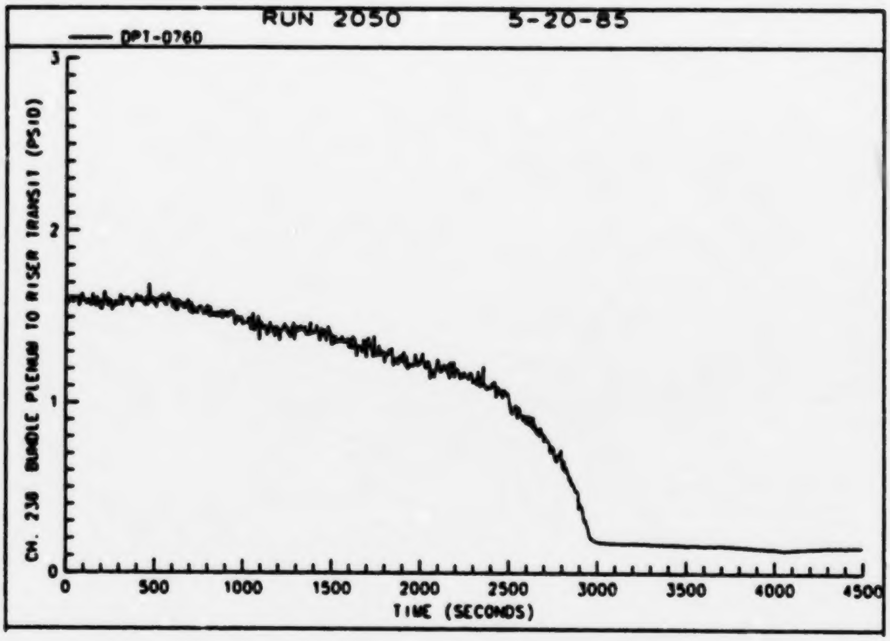

Figure 5-407. Differential Pressure, DP-0760: Test No. 15 (T-2050)

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413

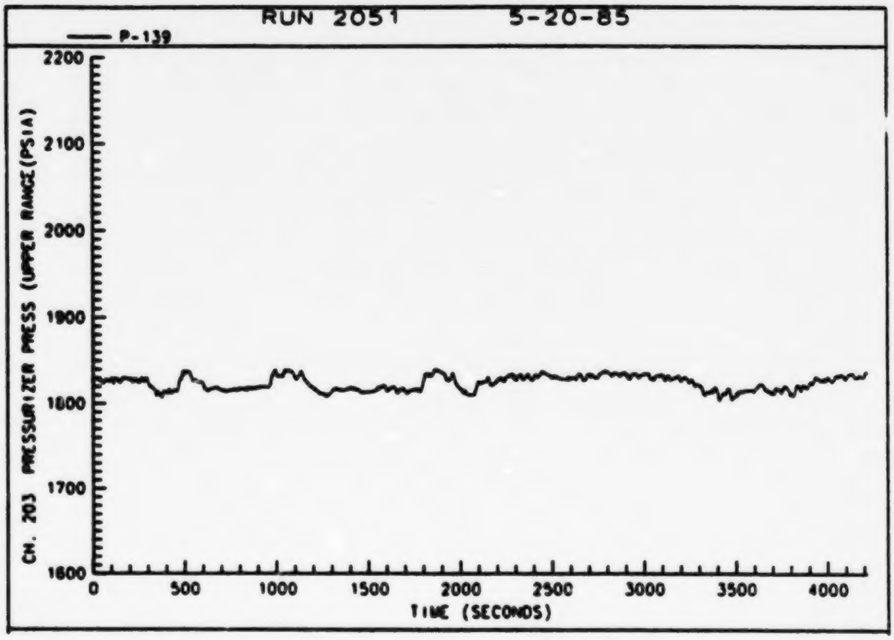

Figure 5-408. Primary System (Pressurizer) Pressure (P-139): Test No. 15 (T-2051)

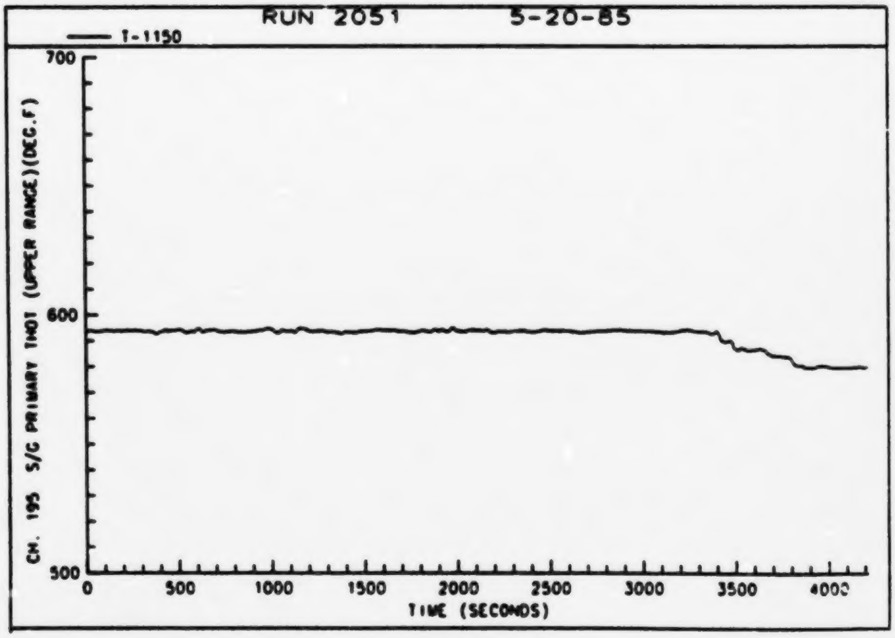

Figure 5-409. Primary Fluid T_{hot} (T-1150): Test No. 15 (T-2051)

414

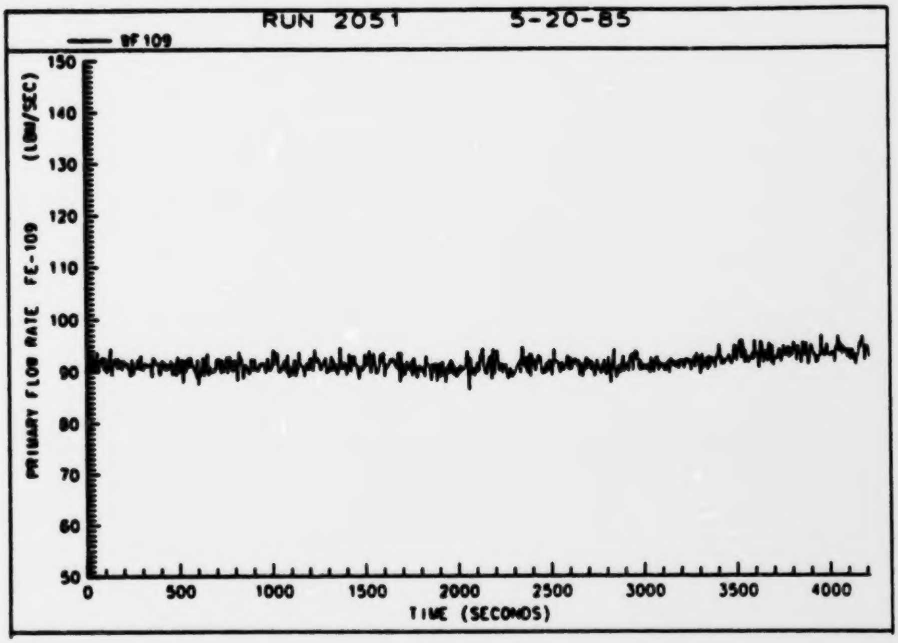

Figure 5-410. Primary Fluid Flow Rate (WF-109): Test No. 15 (T-2051)

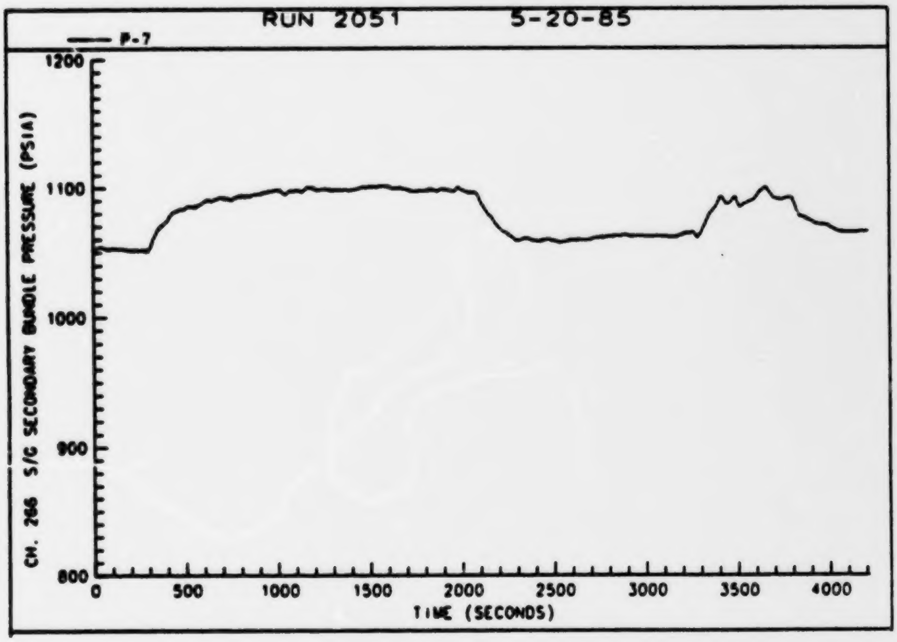

Figure 5-411. Secondary Side Pressure (P-7): Test No. 15 (T-2051)

415

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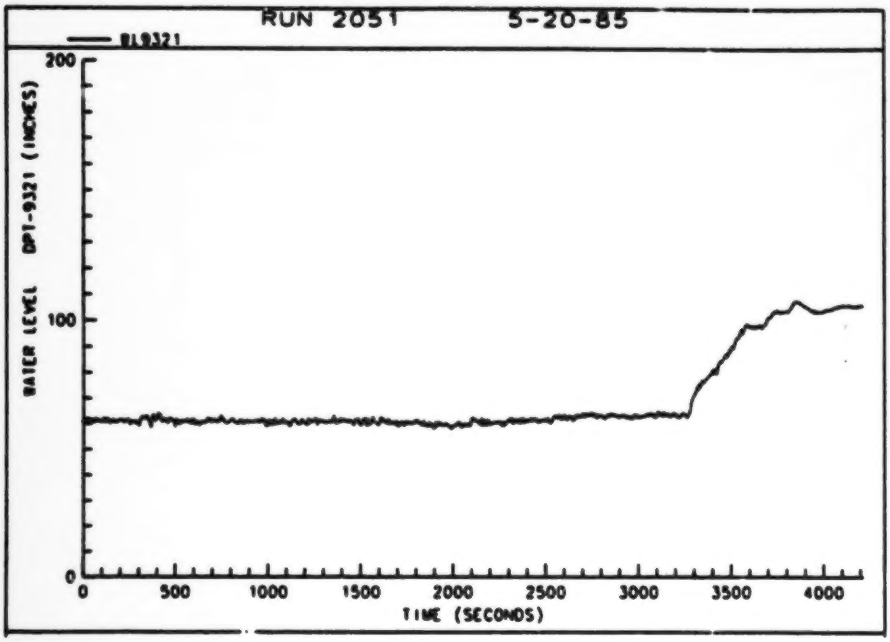

Figure 5-412. Downcomer Water Level - Wide Range (WL-9321): Test No. 15 (T-2051)

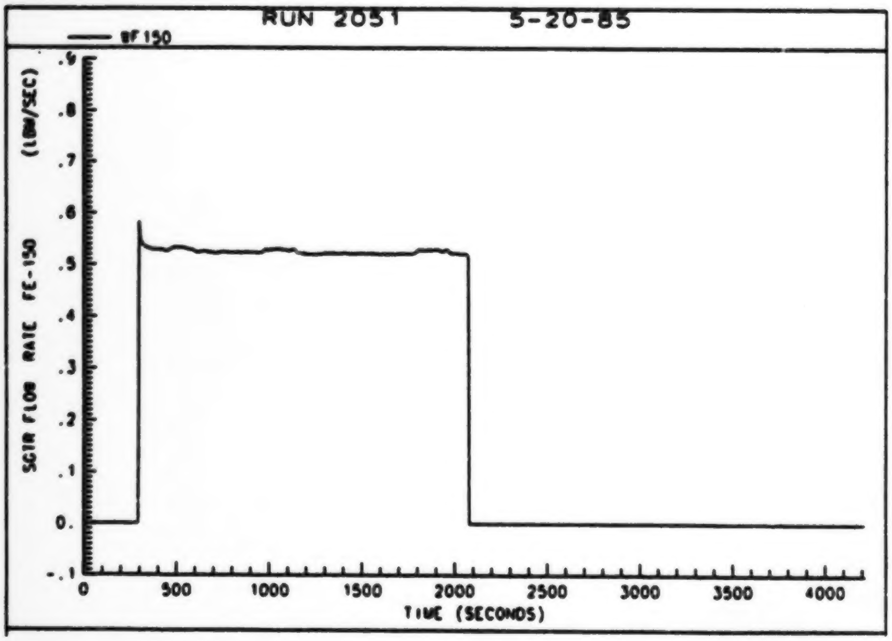

Figure 5-413. SGTR Flow Rate (WF-150): Test No. 15 (T-2051)

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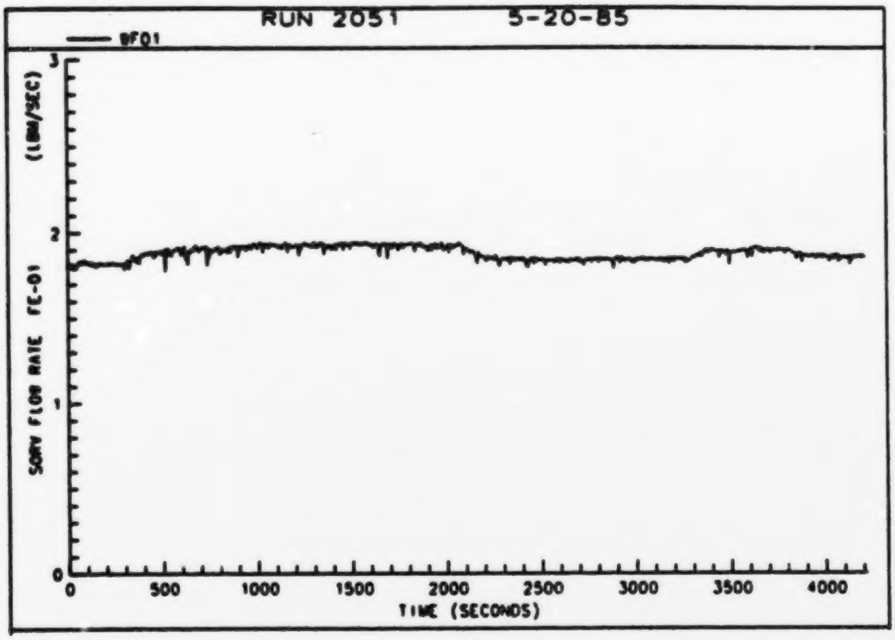

Figure 5-414. SORV Flow Rate (WF-01):
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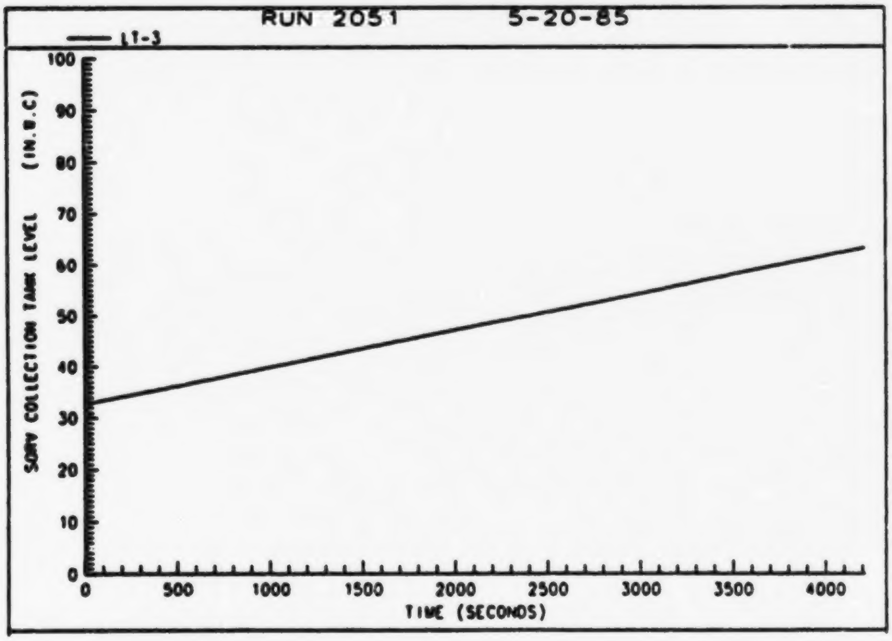

Figure 5-415. SORV Tank Level (LT-3):
Test No. 15 (T-2051)

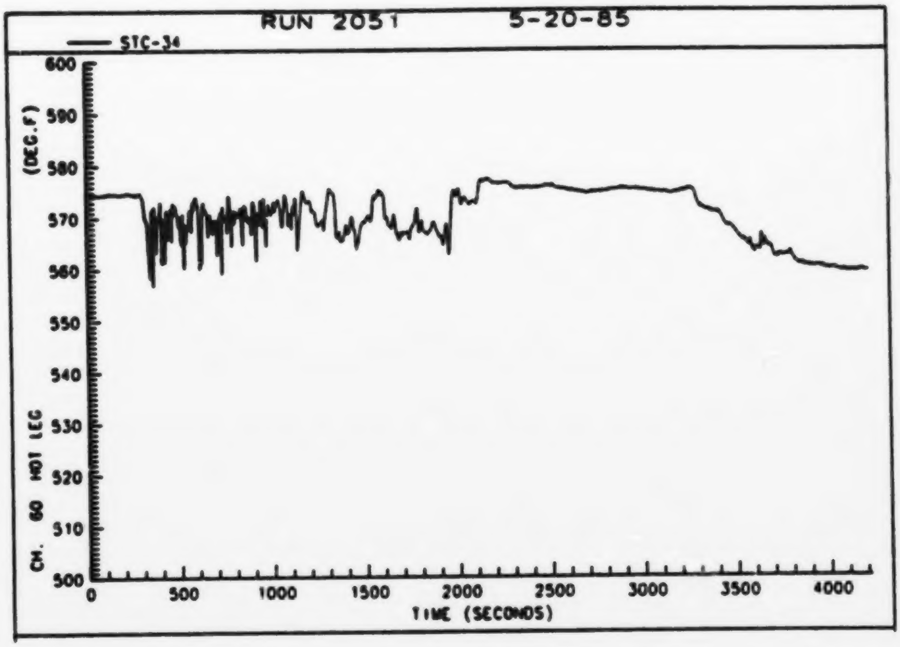

Figure 5-416. Secondary Fluid Temperature (STC-34): Test No. 15 (T-2051)

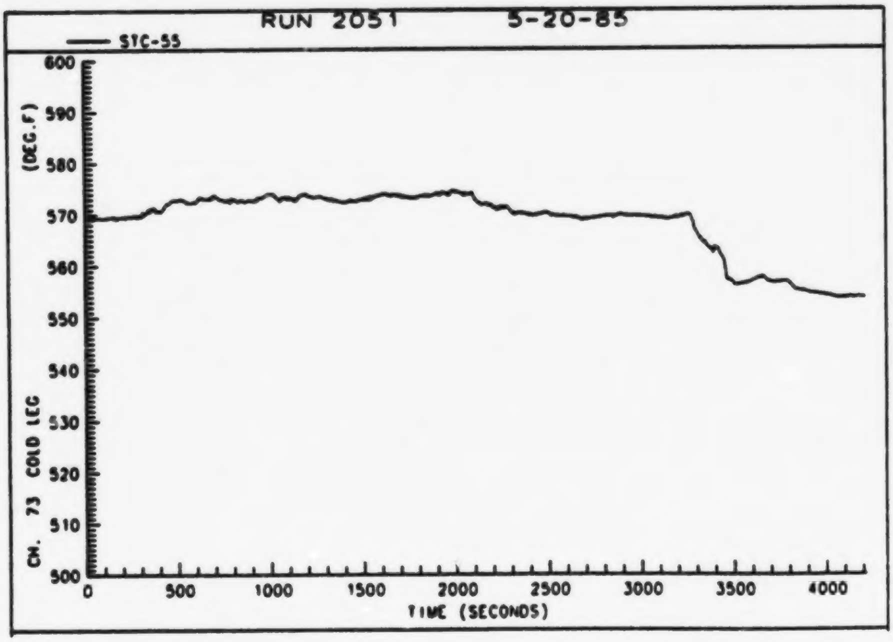

Figure 5-417. Secondary Fluid Temperature (STC-55): Test No. 15 (T-2051)

418

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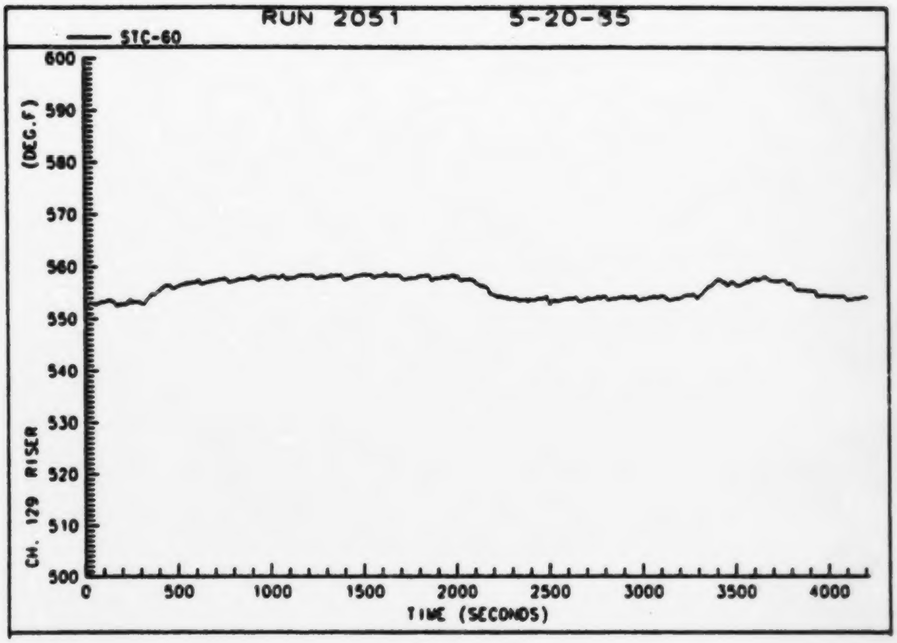

Figure 5-418. Secondary Fluid Temperature (STC-60): Test No. 15 (T-2051)

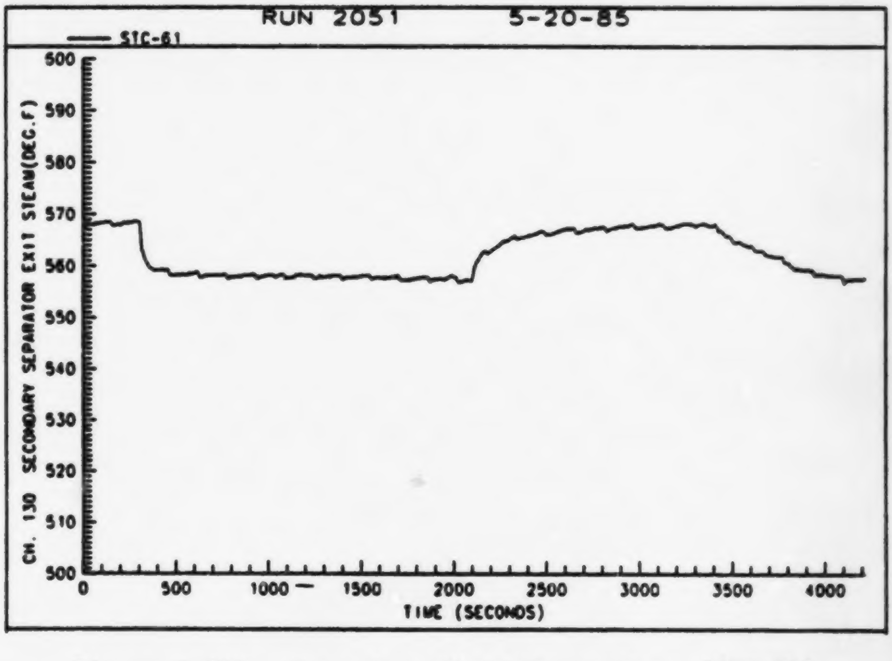

Figure 5-419. Secondary Fluid Temperature (STC-61): Test No. 15 (T-2051)

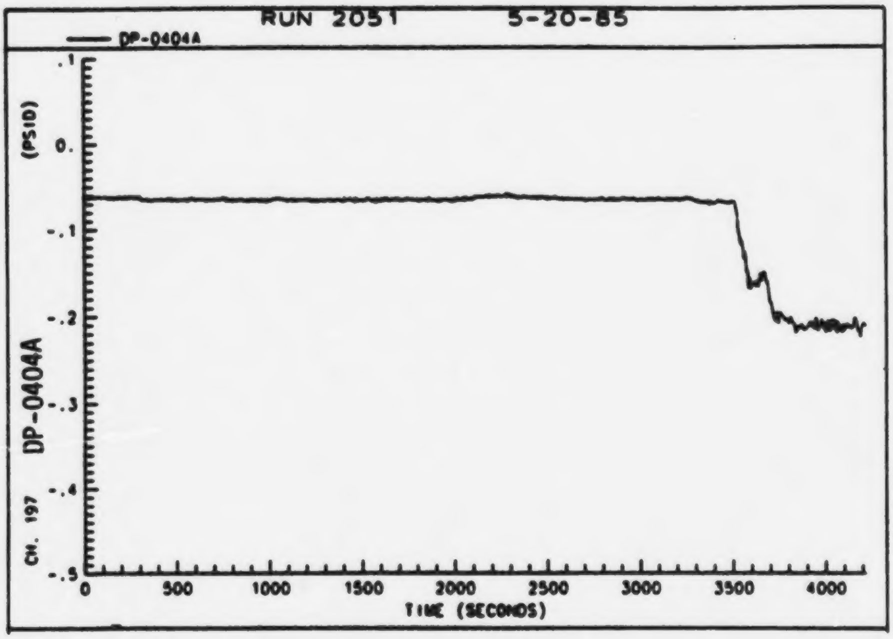

Figure 5-420. Differential Pressure, DP-0404A: Test No. 15 (T-2051)

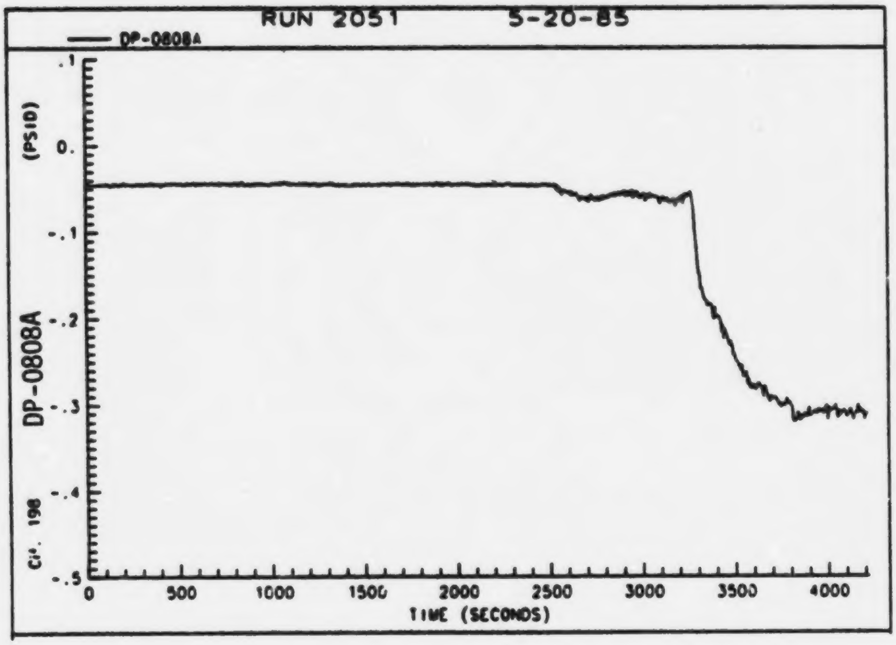

Figure 5-421. Differential Pressure, DP-0808A: Test No. 15 (T-2051)

420

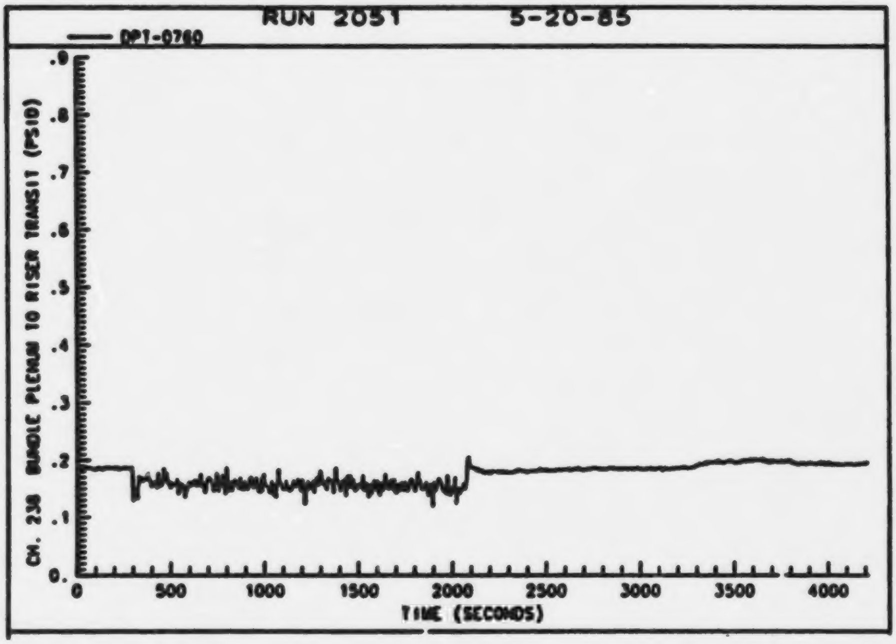

Figure 5-422. Differential Pressure, DP-0760:
Test No. 15 (T-2051)

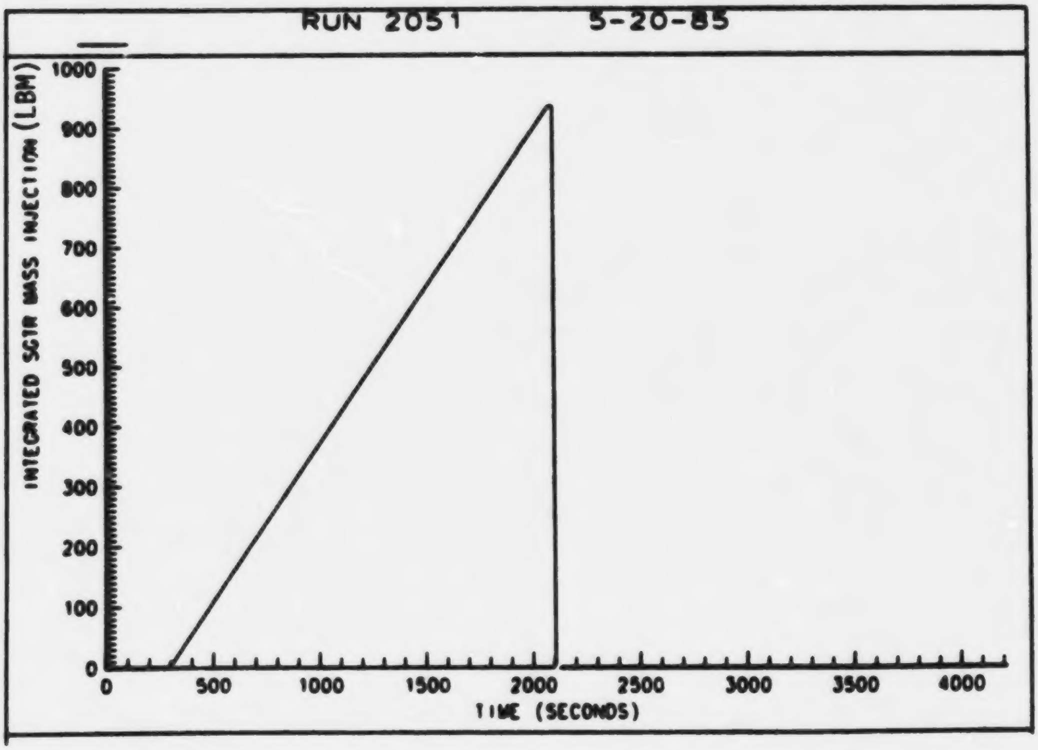

Figure 5-423. Integrated SGTR Flow: Test No. 15 (T-2051)

421

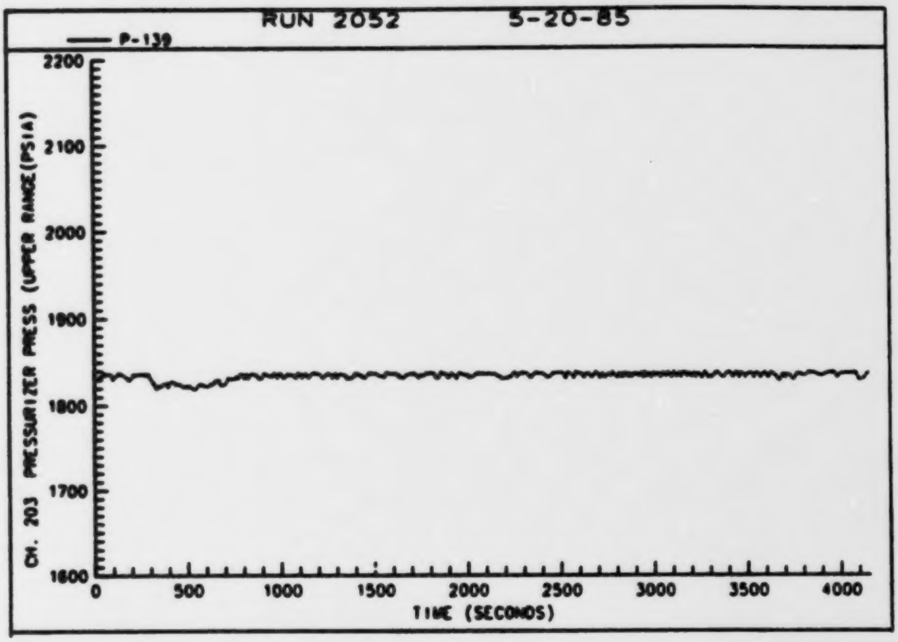

Figure 5-424. Primary System (Pressurizer) Pressure (P-139)
Test No. 15 (T-2052)

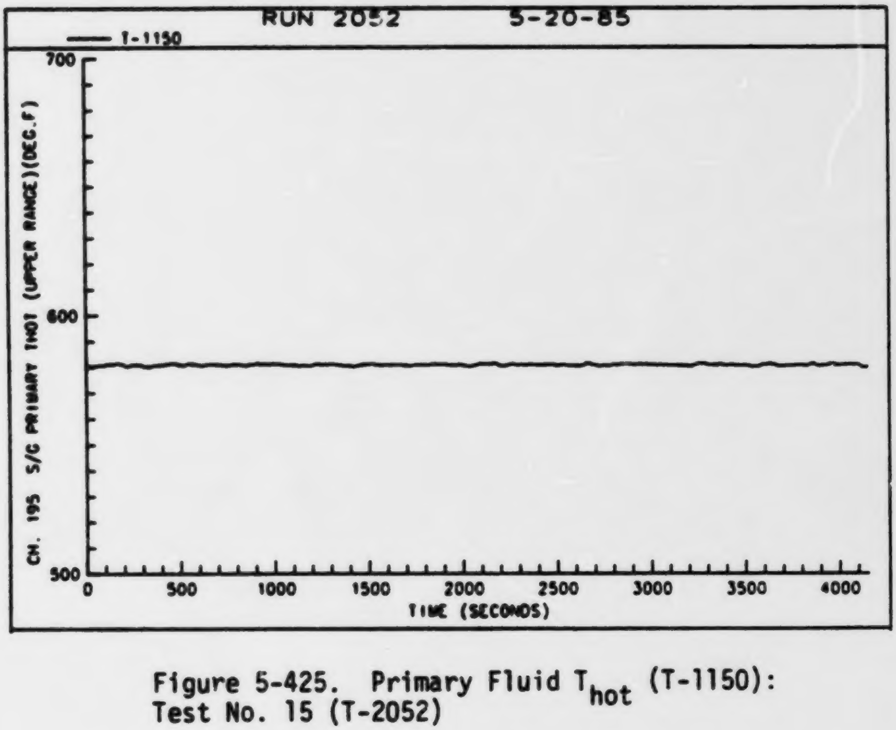

Figure 5-425. Primary Fluid T_{hot} (T-1150):
Test No. 15 (T-2052)

422

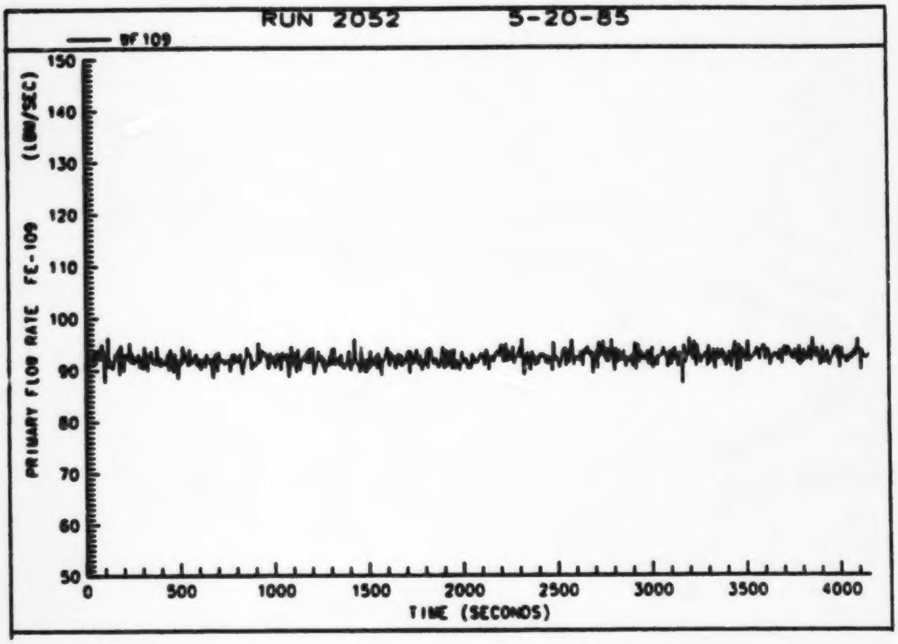

Figure 5-426. Primary Fluid Flow Rate (WF-109): Test No. 15 (T-2052)

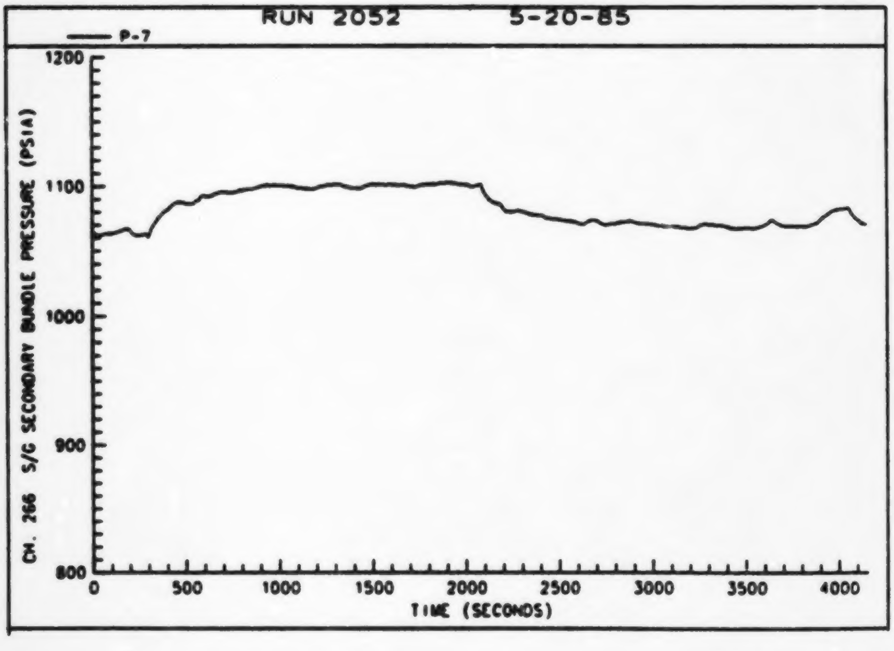

Figure 5-427. Secondary Side Pressure (P-7): Test No. 15 (T-2052)

423

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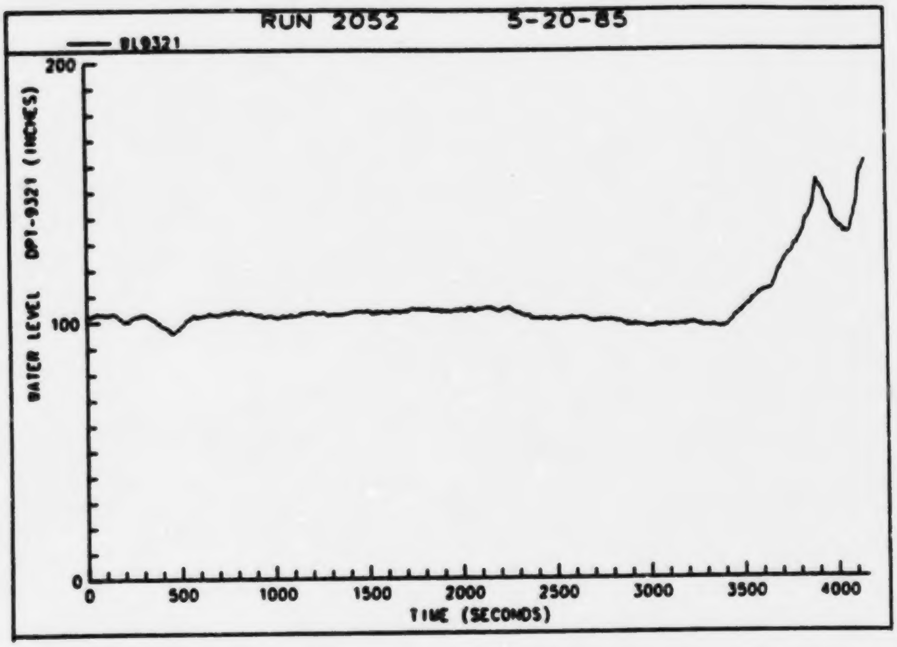

Figure 5-428. Downcomer Water Level - Wide Range (WL-9321): Test No. 15 (T-2052)

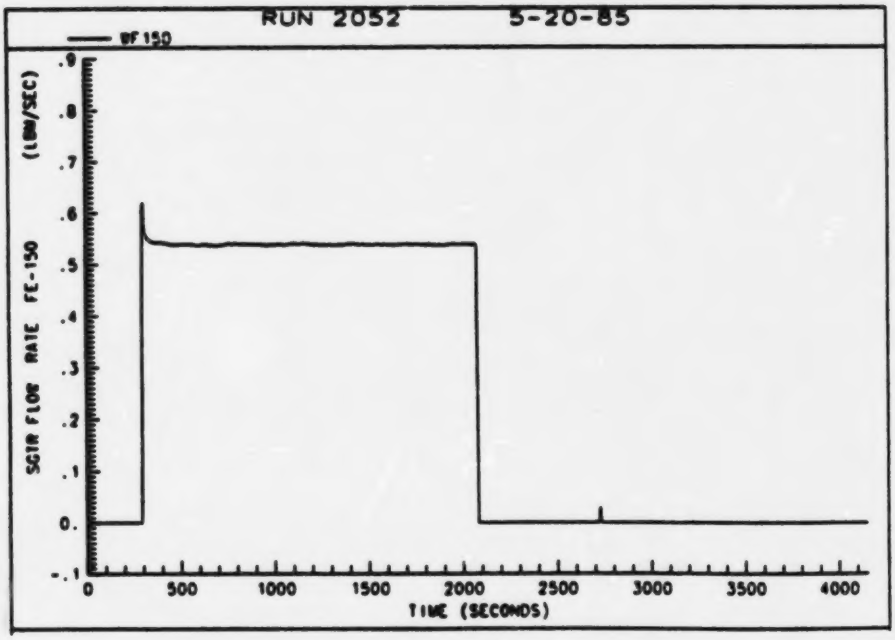

Figure 5-429. SGTR Flow Rate (WF-150): Test No. 15 (T-2052)

424

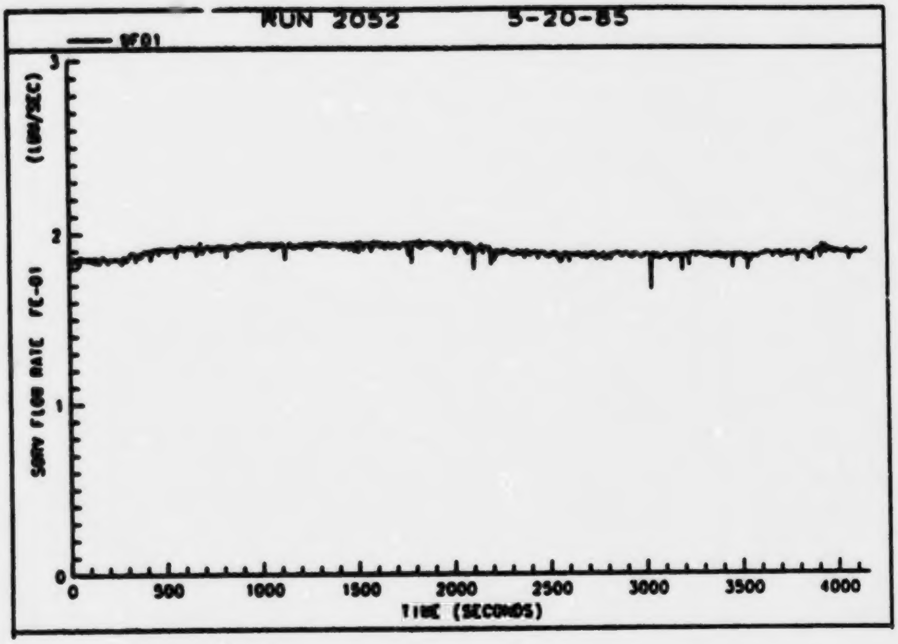

Figure 5-430. SORV Flow Rate (WF-01):
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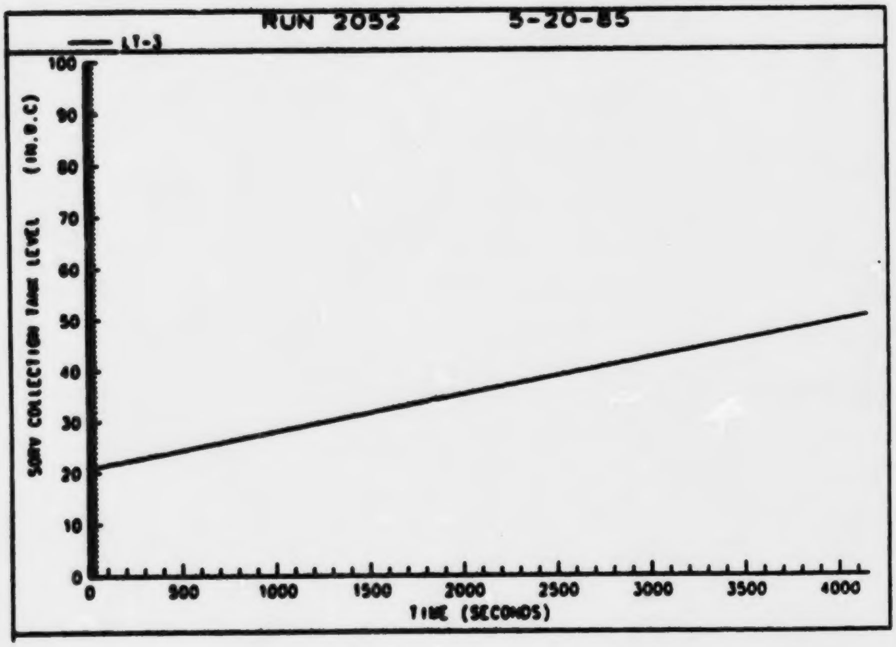

Figure 5-431. SORV Tank Level (LT-3):
Test No. 15 (T-2052)

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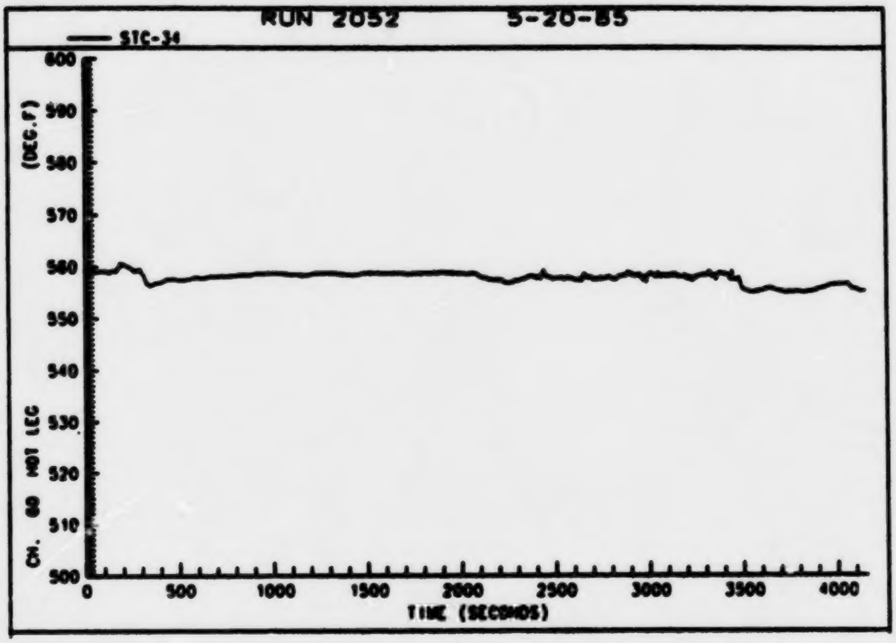

Figure 5-432. Secondary Fluid Temperature (STC-34): Test No. 15 (T-2052)

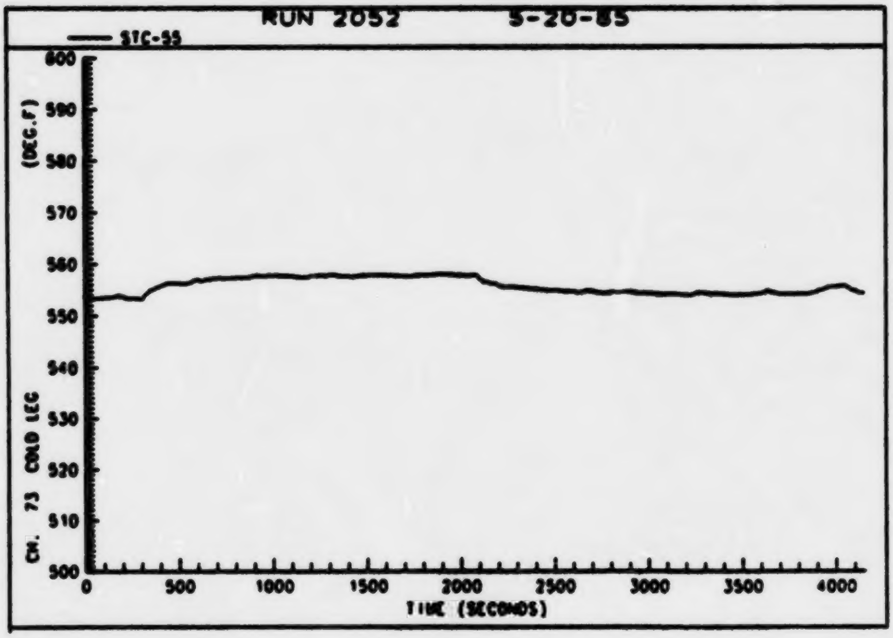

Figure 5-433. Secondary Fluid Temperature (STC-55): Test No. 15 (T-2052)

426

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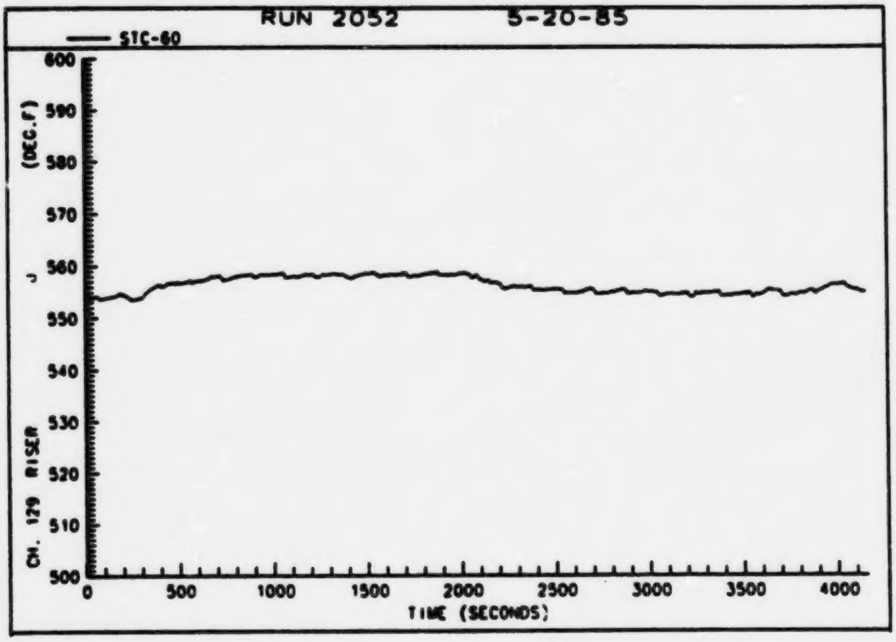

Figure 5-434. Secondary Fluid Temperature (STC-60): Test No. 15 (T-2052)

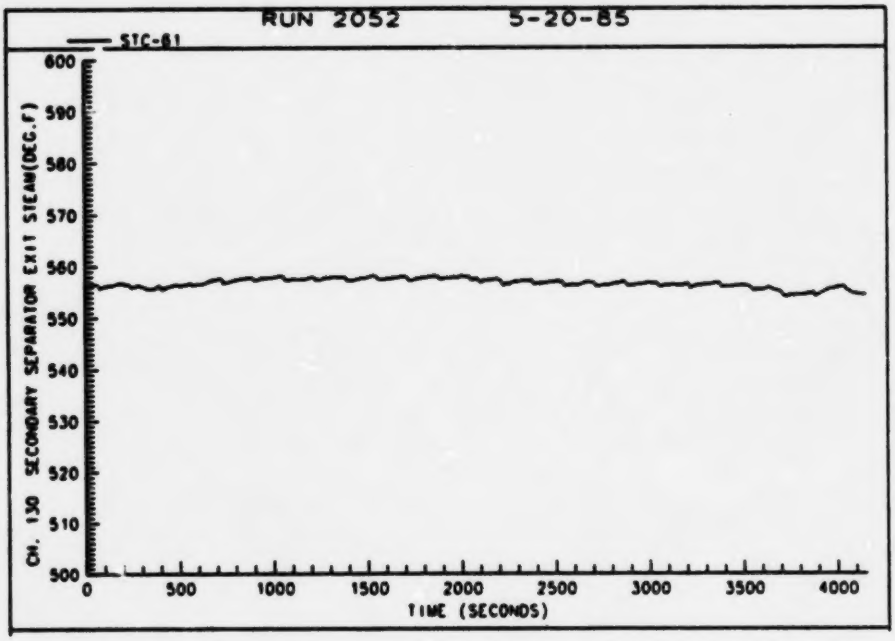

Figure 5-435. Secondary Fluid Temperature (STC-61): Test No. 15 (T-2052)

427

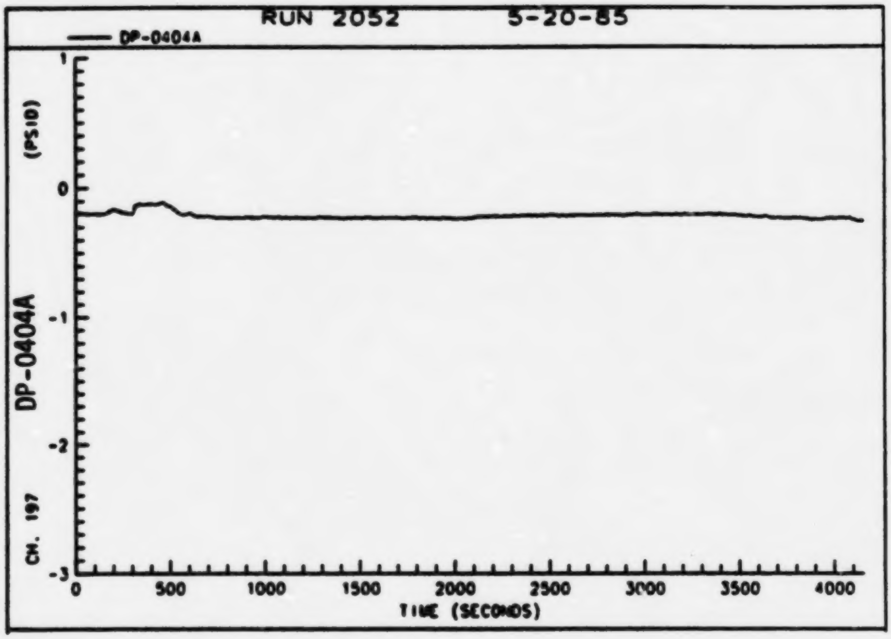

Figure 5-436. Differential Pressure, DP-0404A: Test No. 15 (T-2052)

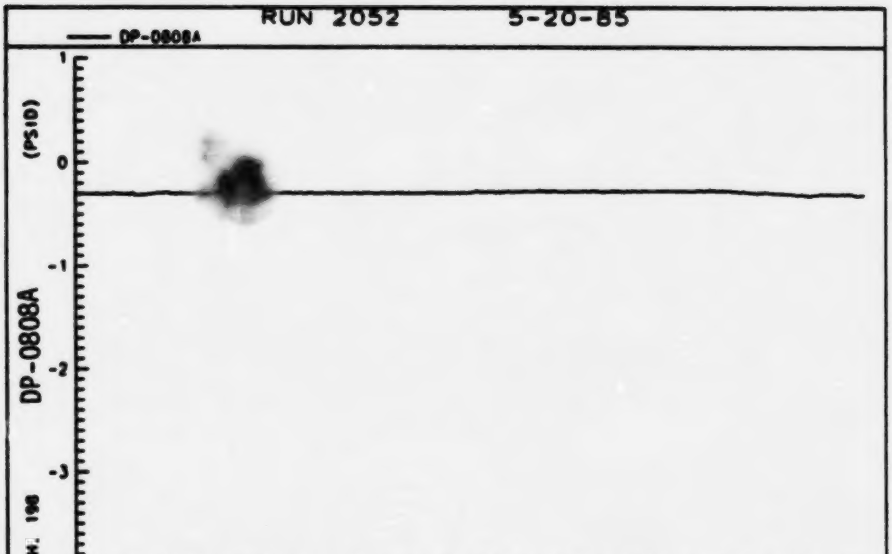

Figure 5-437. Differential Pressure, DP-0808A: Test No. 15 (T-2052)

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428

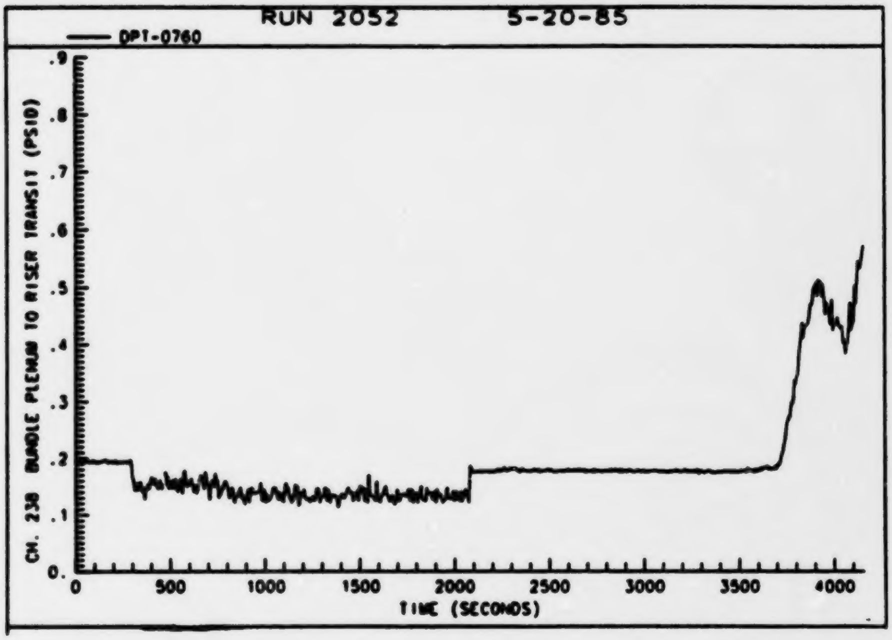

Figure 5-438. Differential Pressure, DP-0760:
Test No. 15 (T-2052)

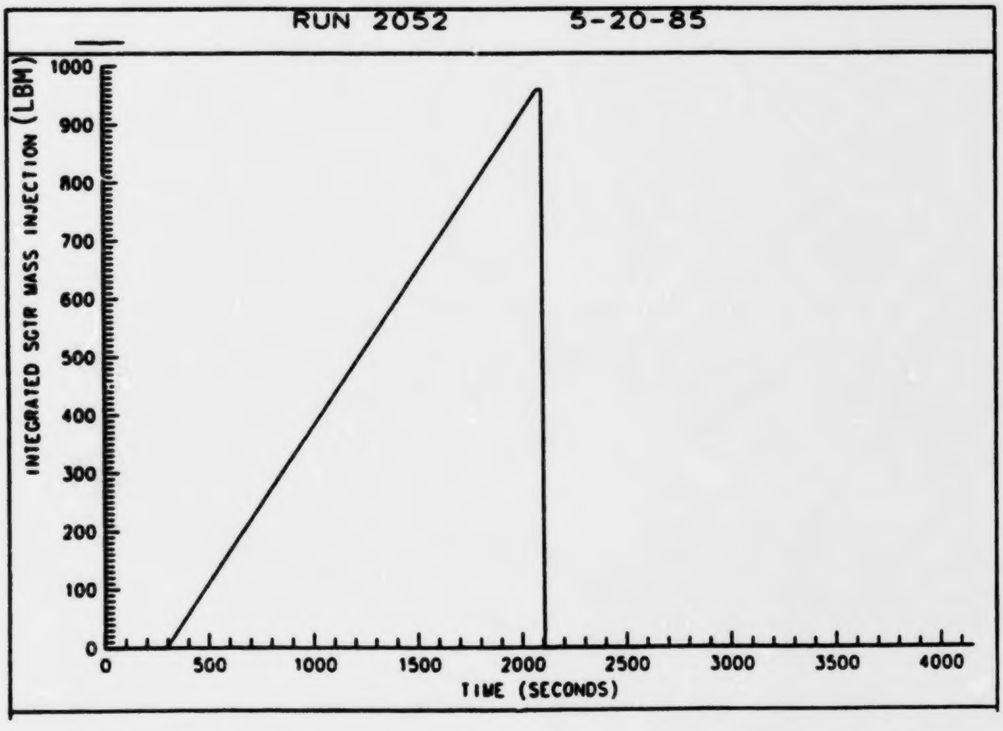

Figure 5-439. Integrated SGTR Flow: Test No. 15 (T-2052)

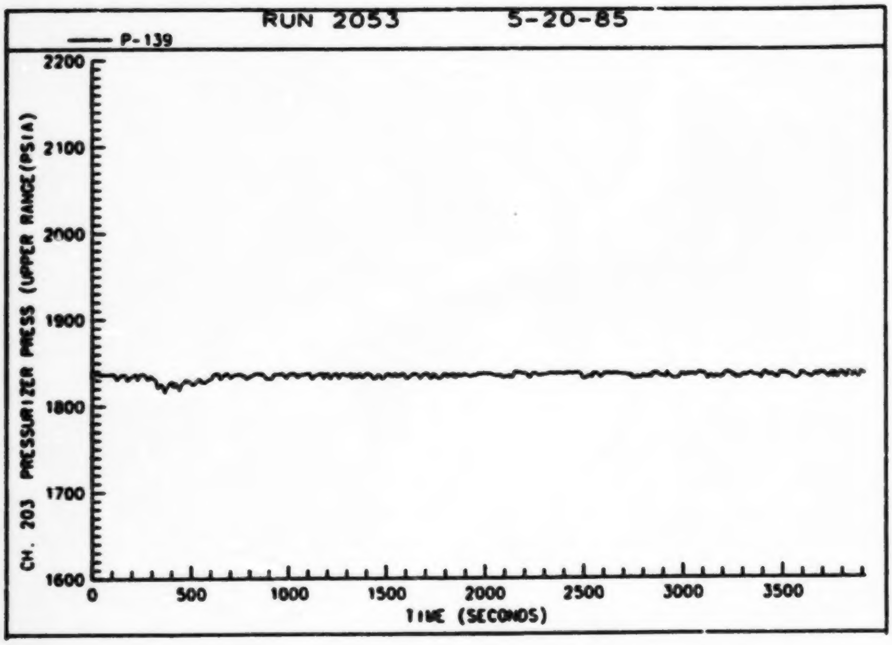

Figure 5-440. Primary System (Pressurizer) Pressure (P-139): Test No. 15 (T-2053)

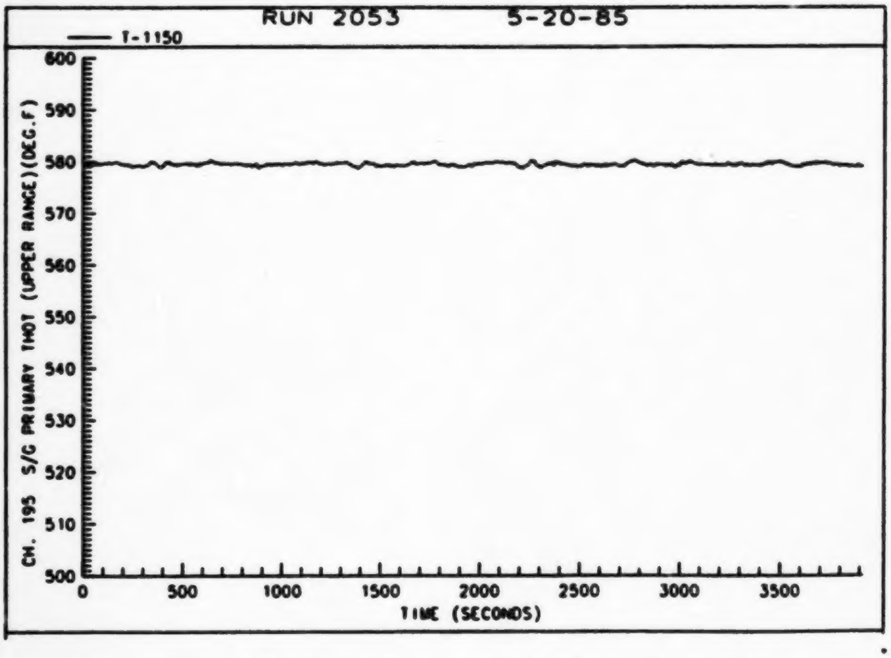

Figure 5-441. Primary Fluid T_{hot} (T-1150): Test No. 15 (T-2053)

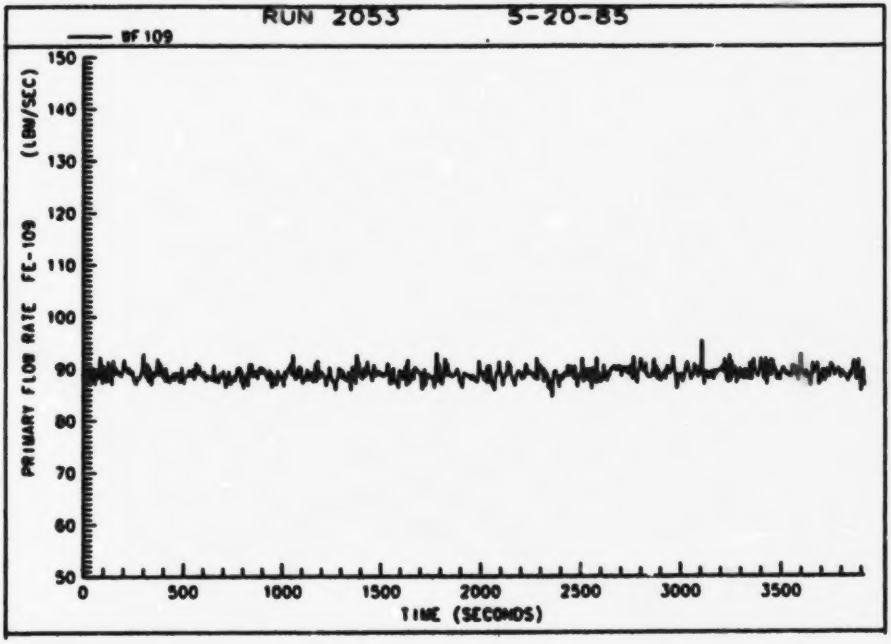

Figure 5-442. Primary Fluid Flow Rate (WF-109): Test No. 15 (T-2053)

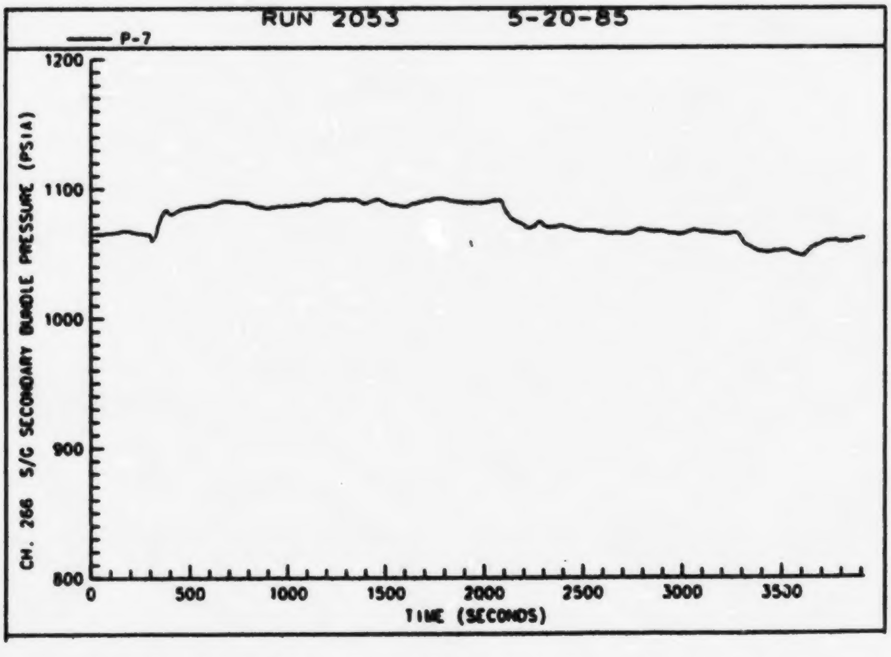

Figure 5-443. Secondary Side Pressure (P-7): Test No. 15 (T-2053)

431

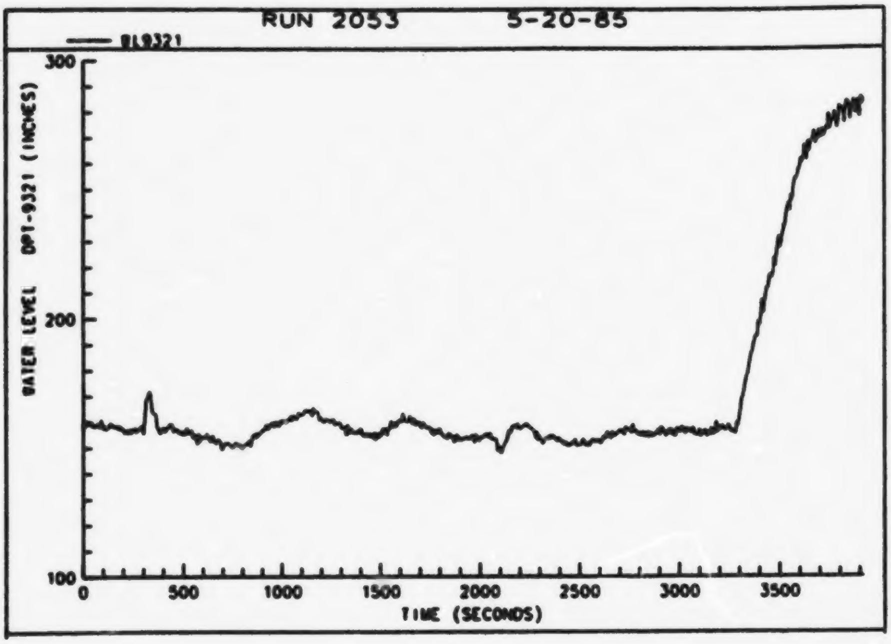

Figure 5-444. Downcomer Water Level - Wide Range (WL-9321): Test No. 15 (T-2053)

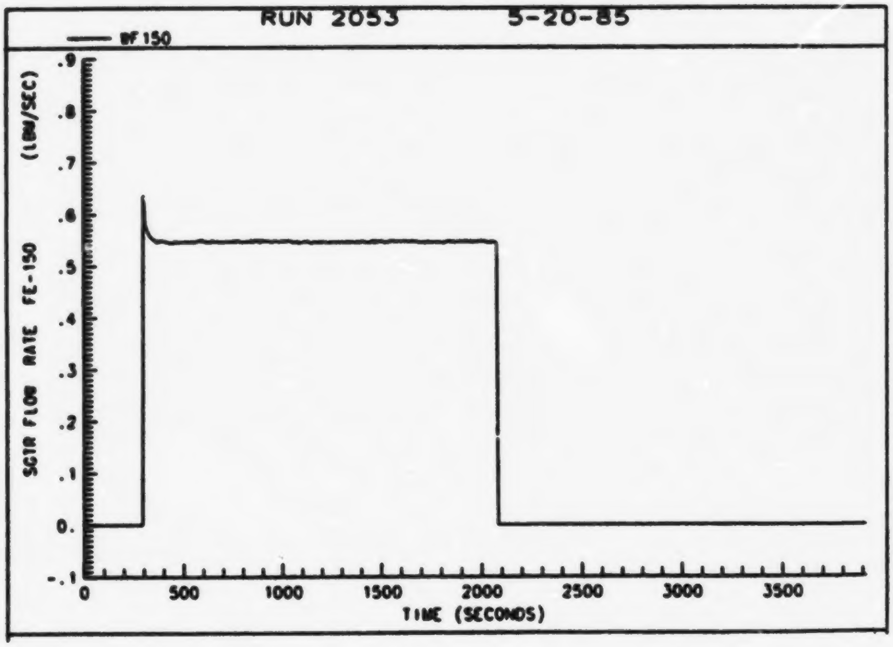

Figure 5-445. SGTR Flow Rate (WF-150): Test No. 15 (T-2053)

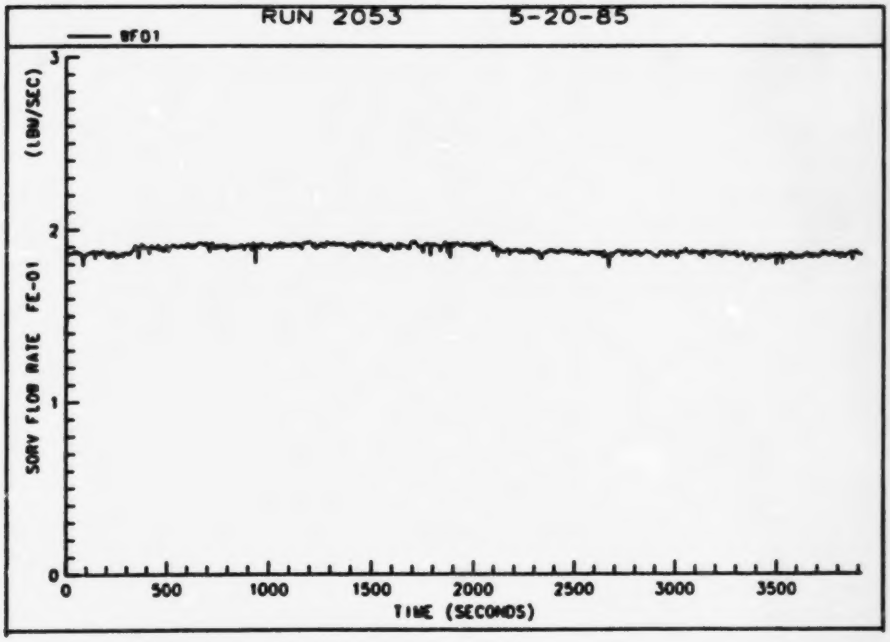

Figure 5-446. SORV Flow Rate (WF-01):
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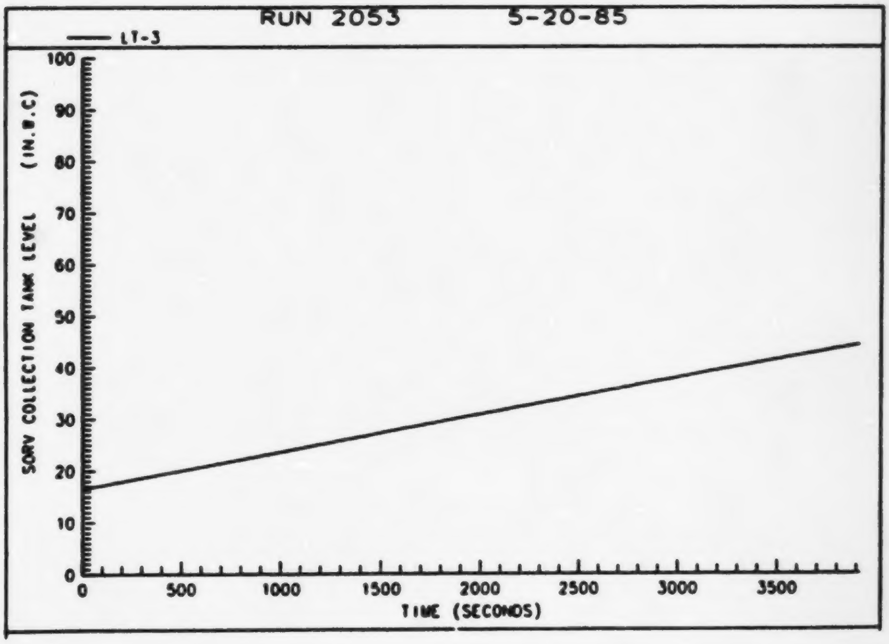

Figure 5-447. SORV Tank Level (LT-3):
Test No. 15 (T-2053)

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433

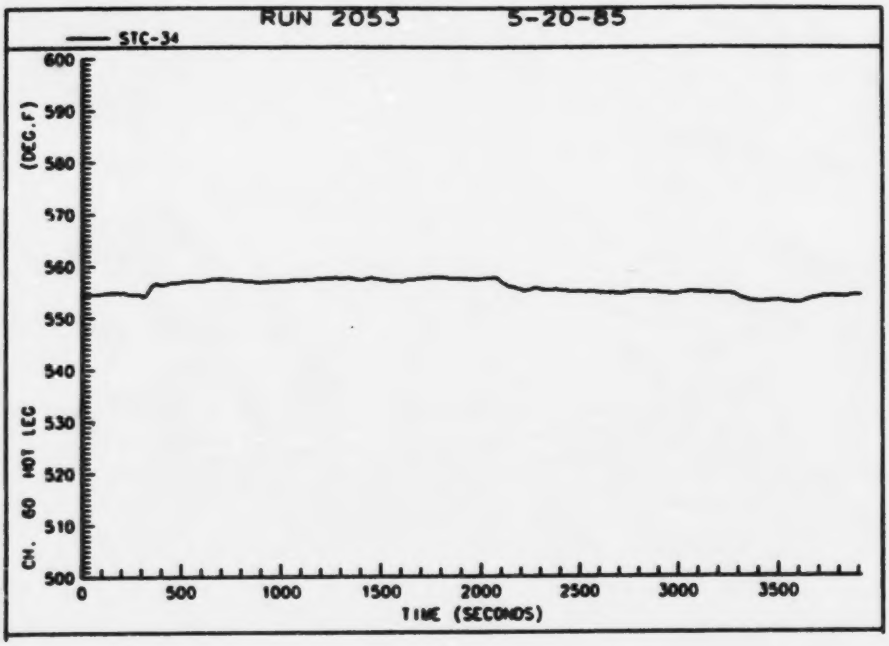

Figure 5-448. Secondary Fluid Temperature (STC-34): Test No. 15 (T-2053)

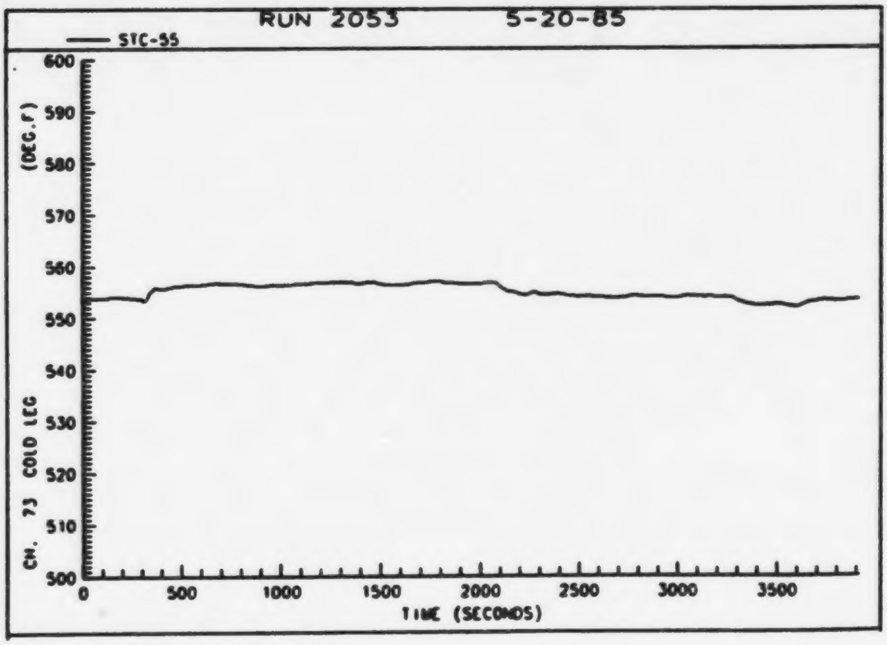

Figure 5-449. Secondary Fluid Temperature (STC-55): Test No. 15 (T-2053)

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434

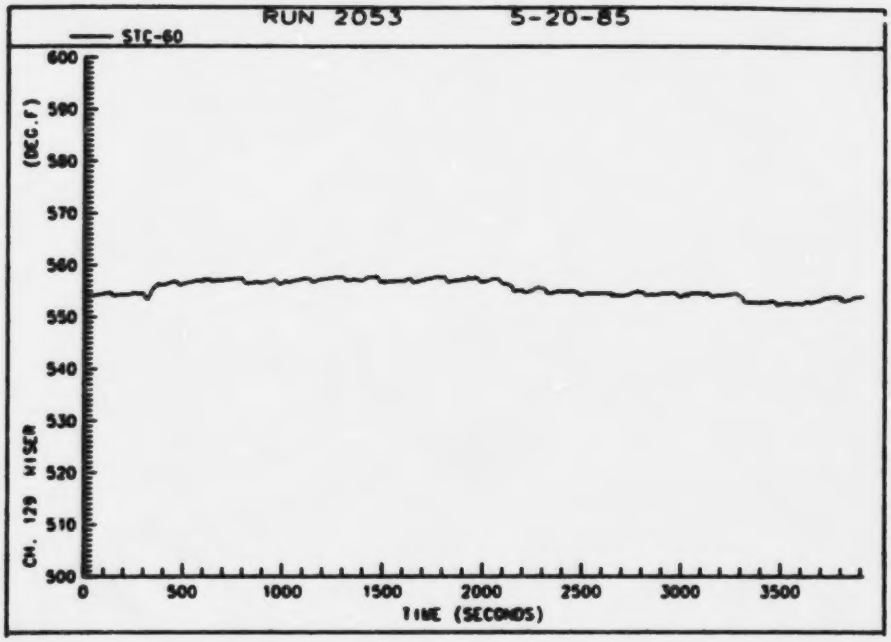

Figure 5-450. Secondary Fluid Temperature (STC-60): Test No. 15 (T-2053)

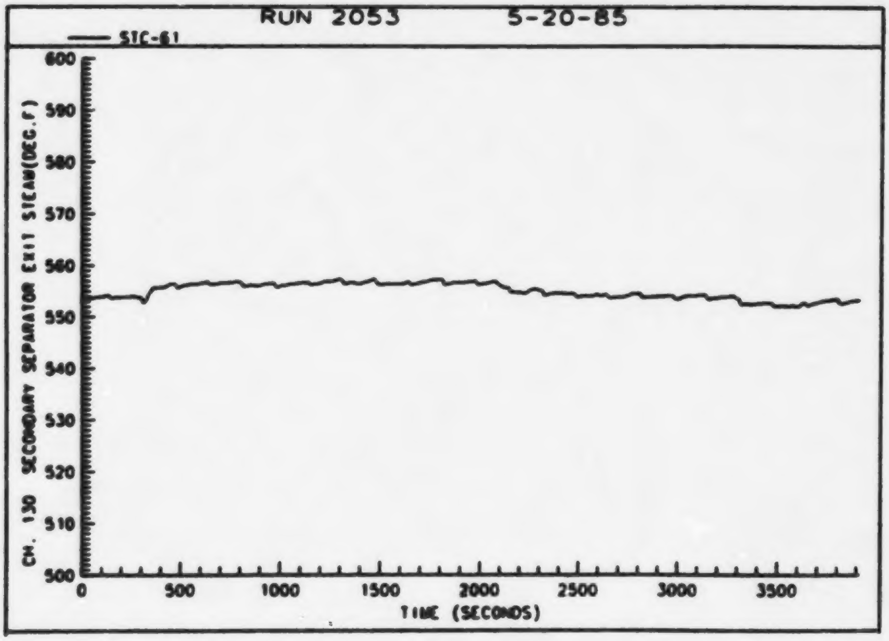

Figure 5-451. Secondary Fluid Temperature (STC-61): Test No. 15 (T-2053)

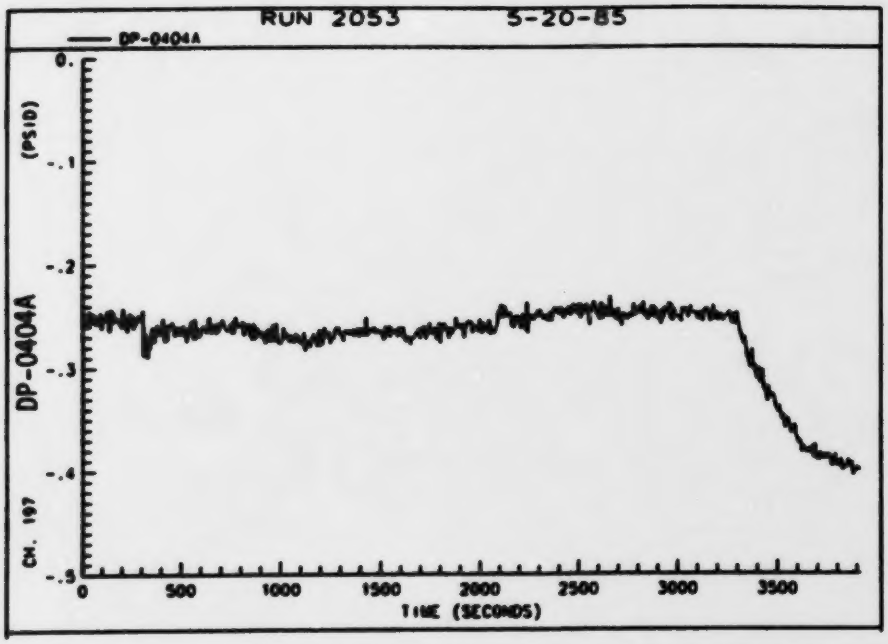

Figure 5-452. Differential Pressure, DP-0404A: Test No. 15 (T-2053)

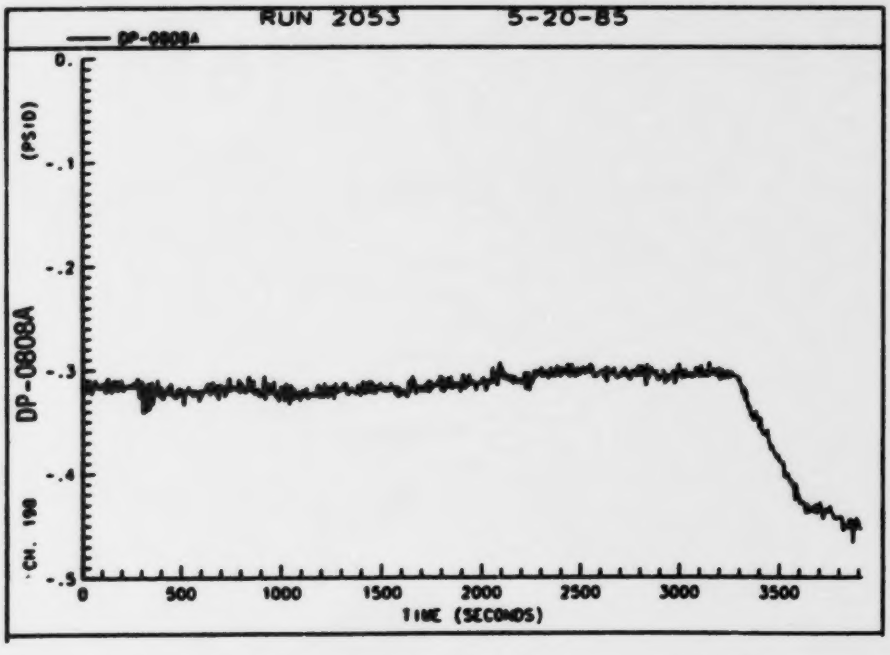

Figure 5-453. Differential Pressure, DP-0808A: Test No. 15 (T-2053)

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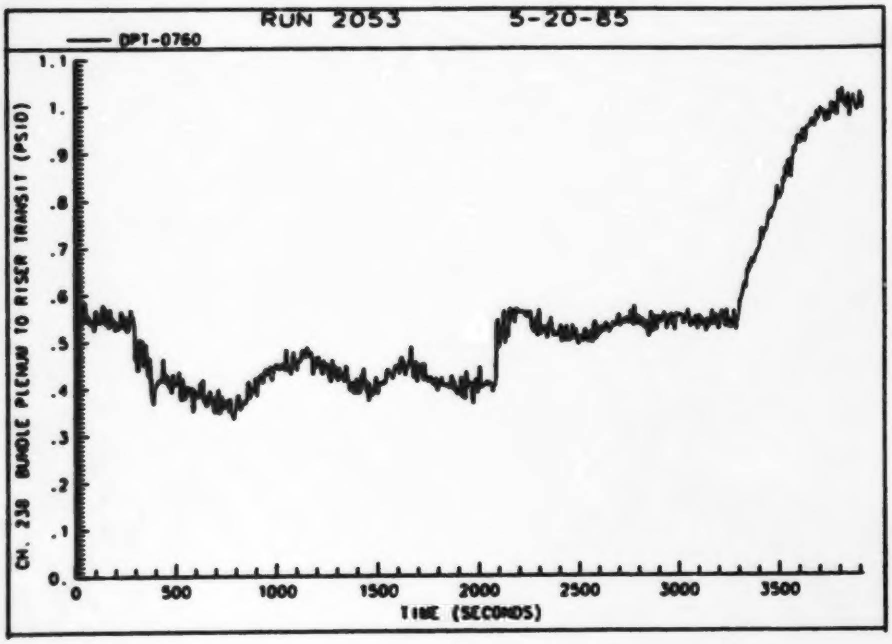

Figure 5-454. Differential Pressure, DP-0760: Test No. 15 (T-2053)

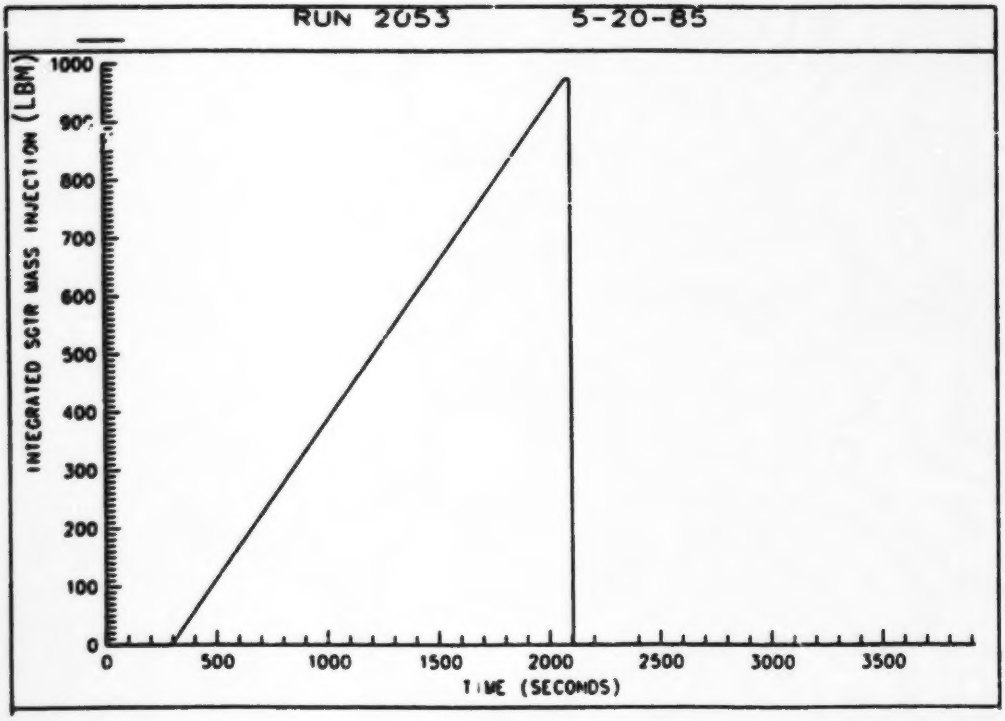

Figure 5-455. Integrated SGTR Flow: Test No. 15 (T-2053)

437

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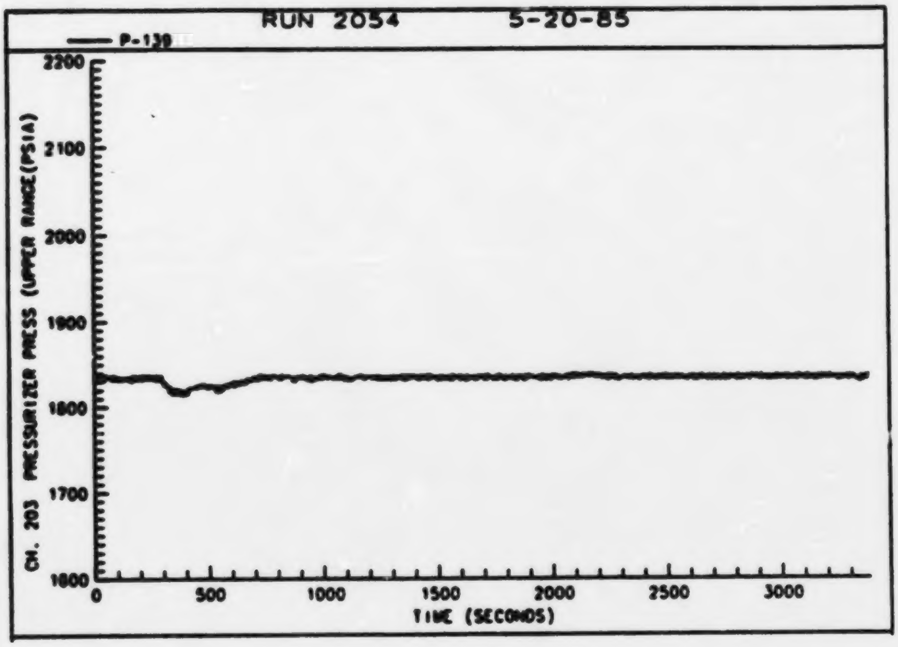

Figure 5-456. Primary System (Pressurizer) Pressure (P-139): Test No. 15 (T-2054)

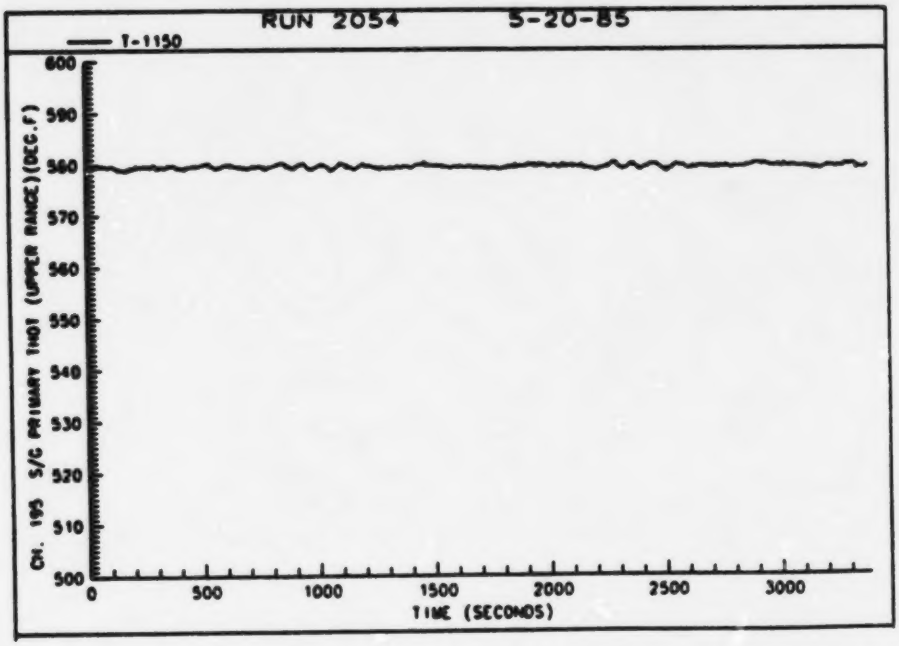

Figure 5-457. Primary Fluid T_{hot} (T-1150): Test No. 15 (T-2054)

438

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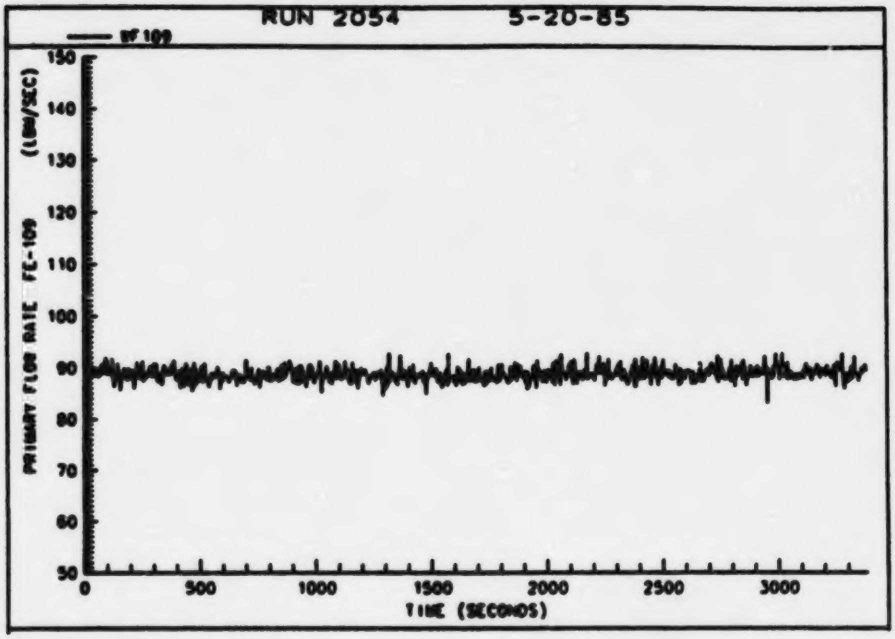

Figure 5-458. Primary Fluid Flow Rate (WF-109): Test No. 15 (T-2054)

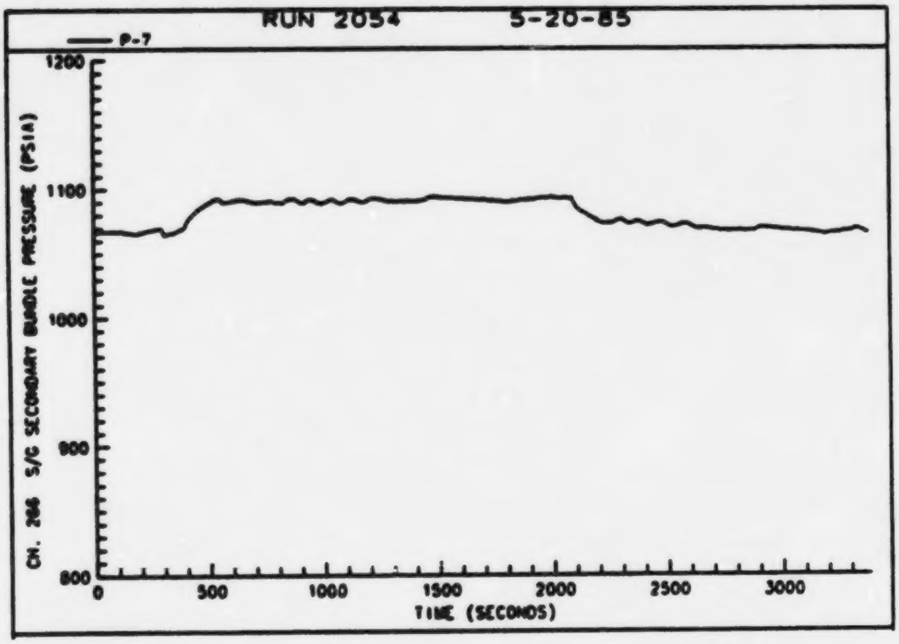

Figure 5-459. Secondary Side Pressure (P-7): Test No. 15 (T-2054)

439

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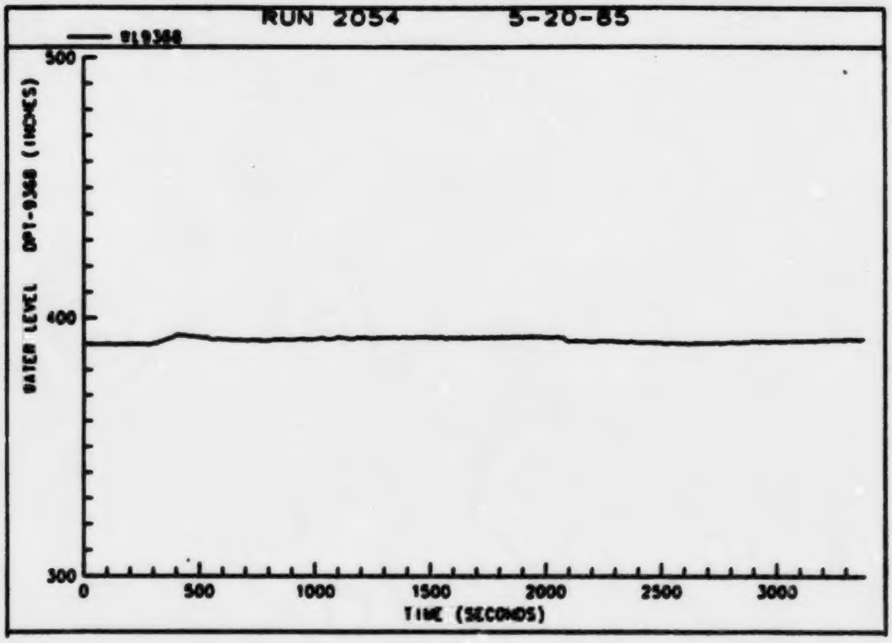

Figure 5-460. Downcomer Water Level - Narrow Range (WL-9368): Test No. 15 (T-2054)

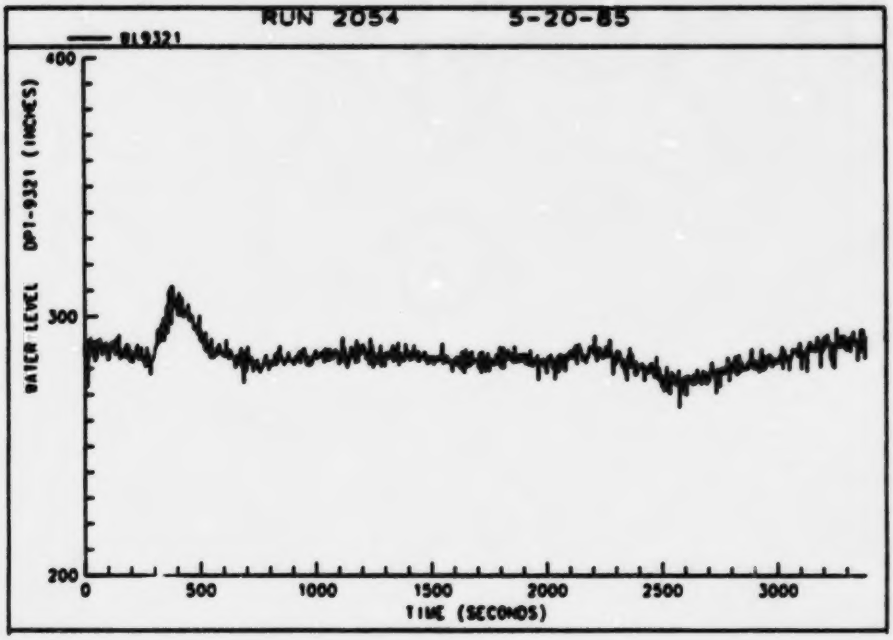

Figure 5-461. Downcomer Water Level - Wide Range (WL-9321): Test No. 15 (T-2054)

440

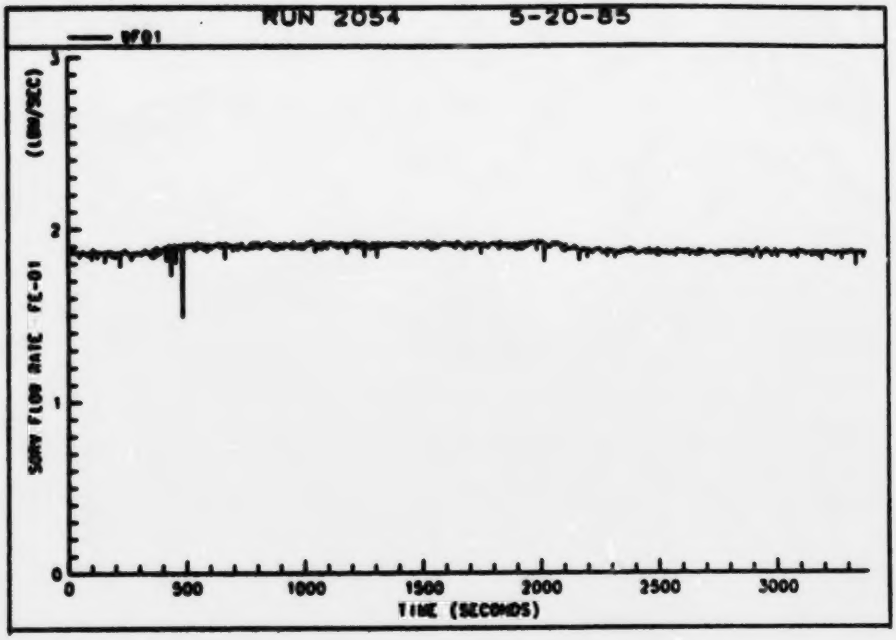

Figure 5-462. SORV Flow Rate (WF-01):
Test No. 15 (T-2054)

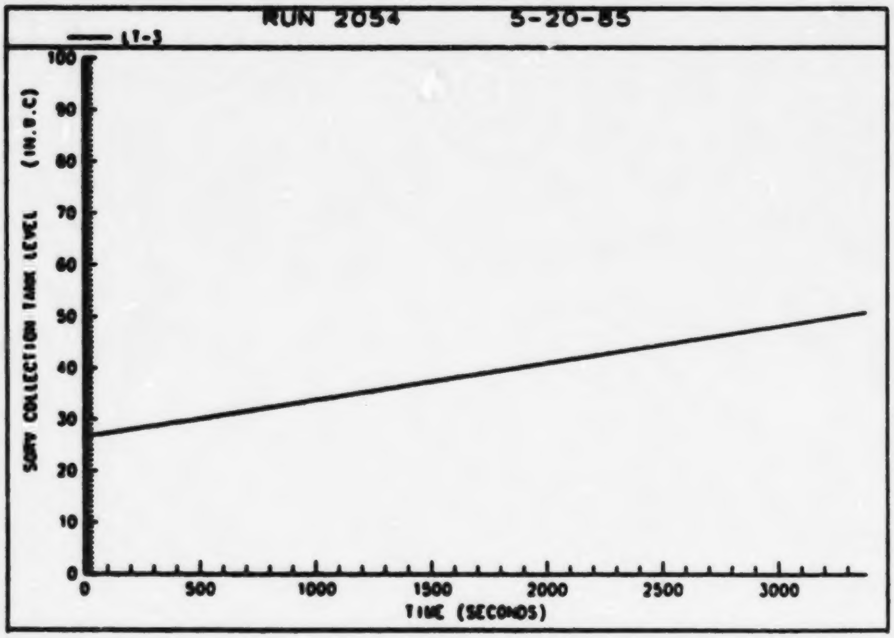

Figure 5-463. SORV Tank Level (LT-3):
Test No. 15 (T-2054)

441

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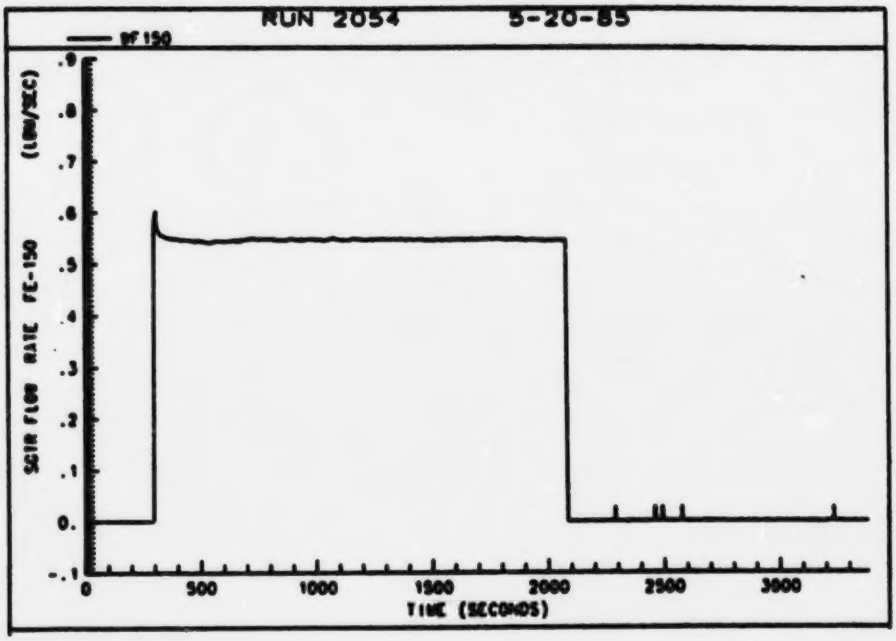

Figure 5-464. SGTR Flow Rate (WF-150):
Test No. 15 (T-2054)

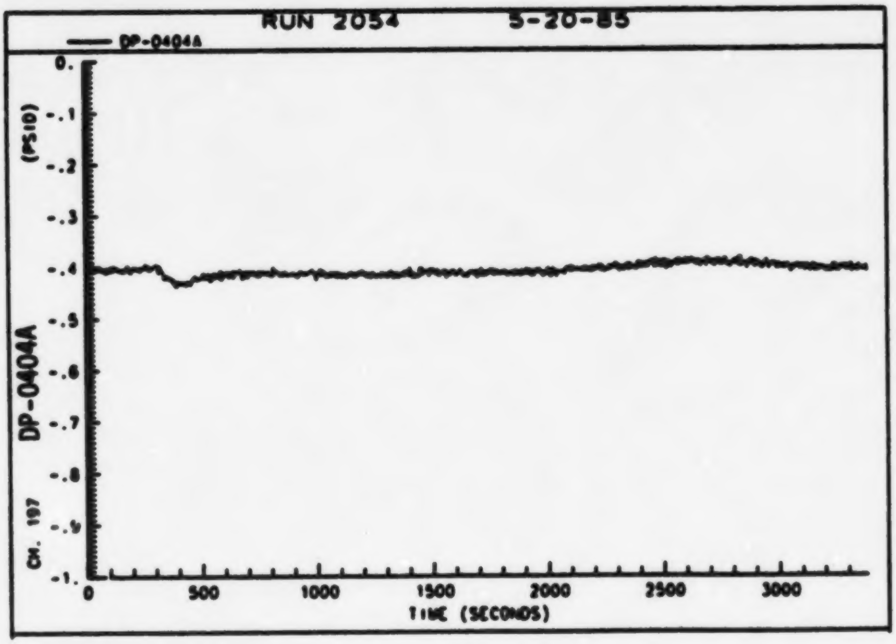

Figure 5-465. Differential Pressure, DP-0404A:
Test No. 15 (T-2054)

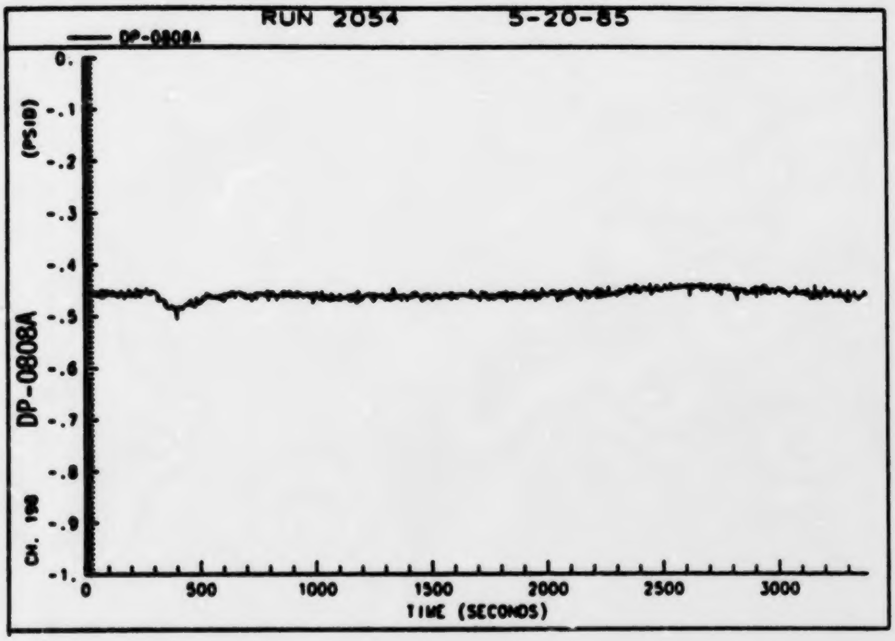

Figure 5-466. Differential Pressure, DP-0808A: Test No. 15 (T-2054)

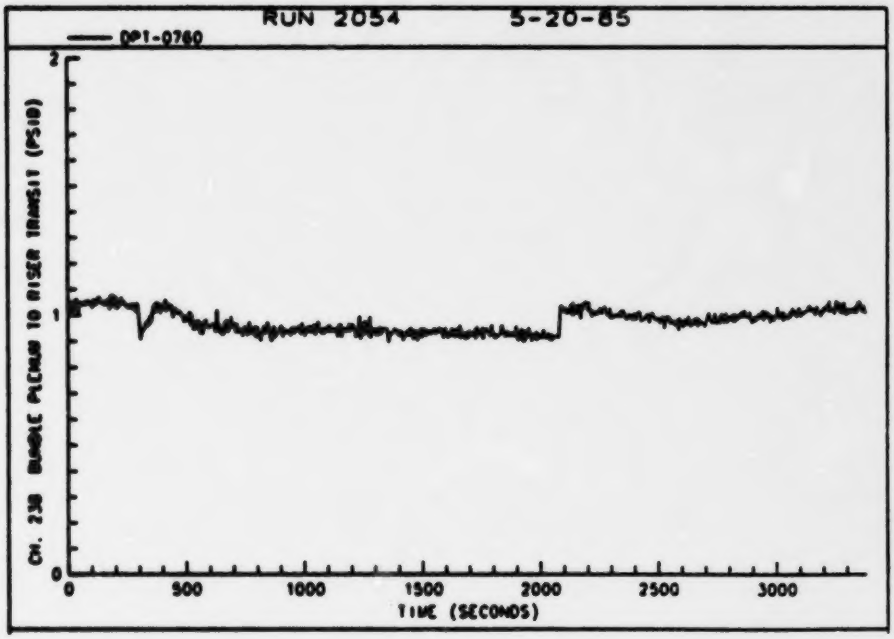

Figure 5-467. Differential Pressure, DP-0760: Test No. 15 (T-2054)

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443

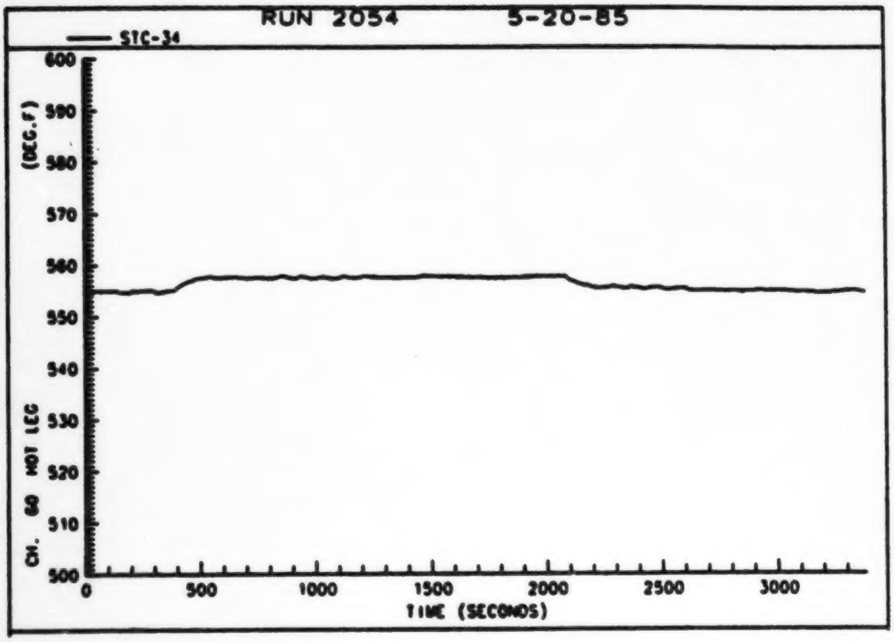

Figure 5-468. Secondary Fluid Temperature (STC-34): Test No. 15 (T-2054)

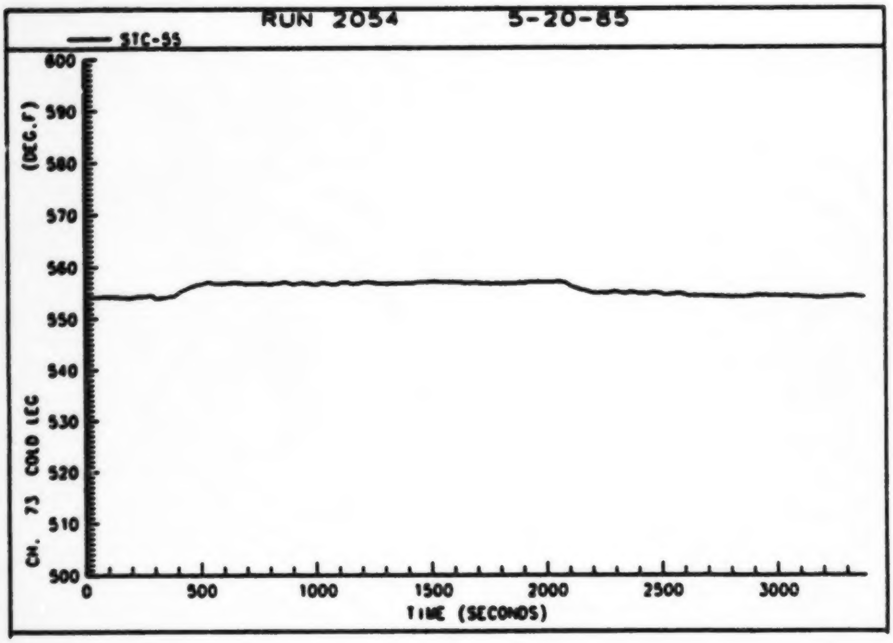

Figure 5-469. Secondary Fluid Temperature (STC-55): Test No. 15 (T-2054)

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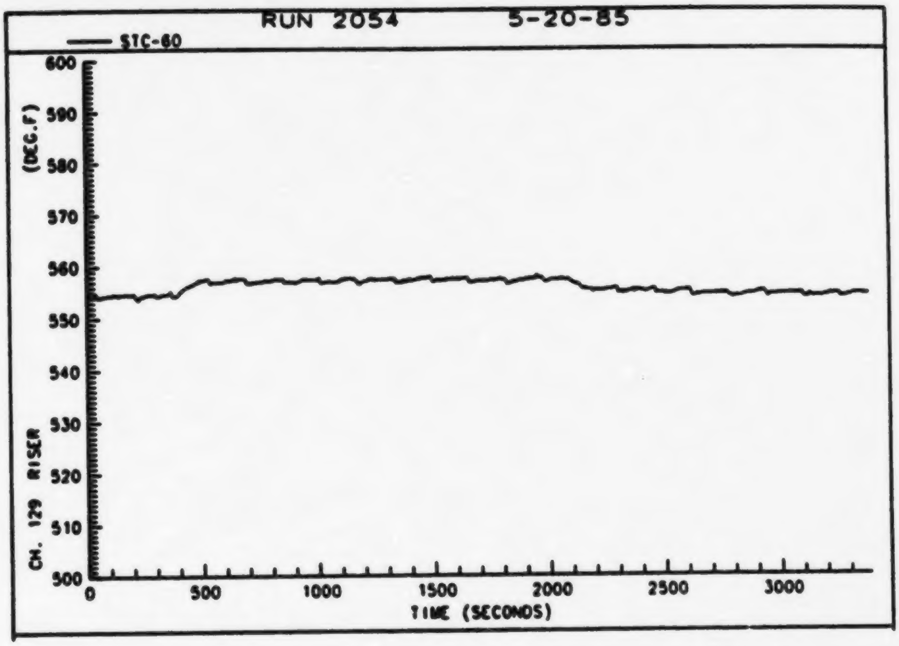

Figure 5-470. Secondary Fluid Temperature (STC-60): Test No. 15 (T-2054)

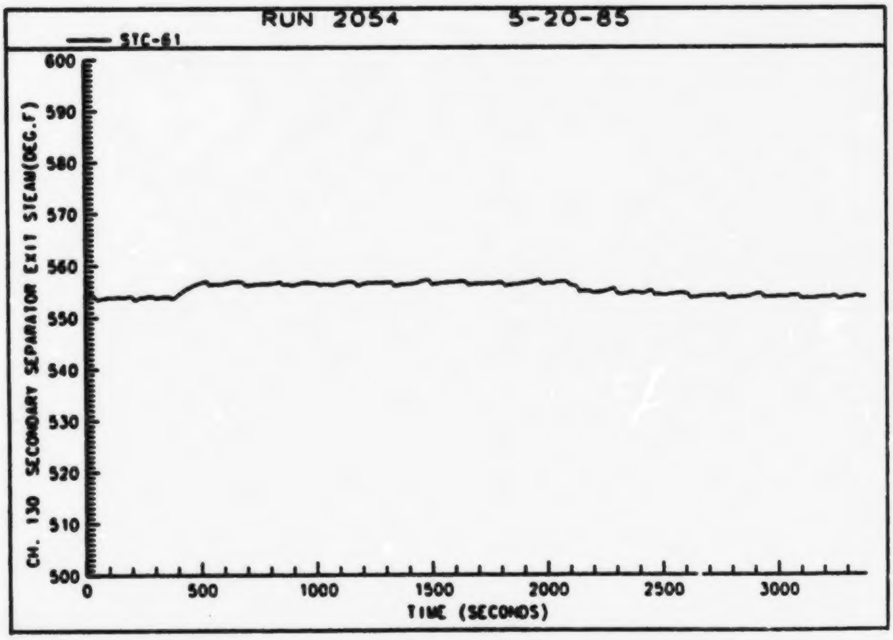

Figure 5-471. Secondary Fluid Temperature (STC-61): Test No. 15 (T-2054)

445

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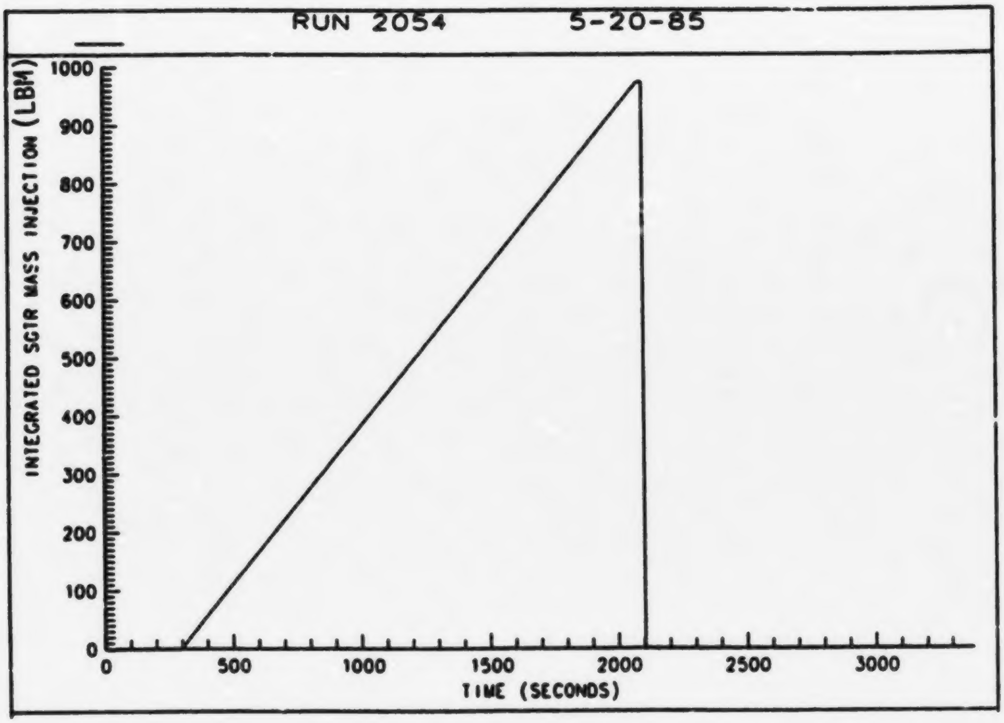

Figure 5-472. Integrated SGTR Flow: Test No. 15 (T-2054)

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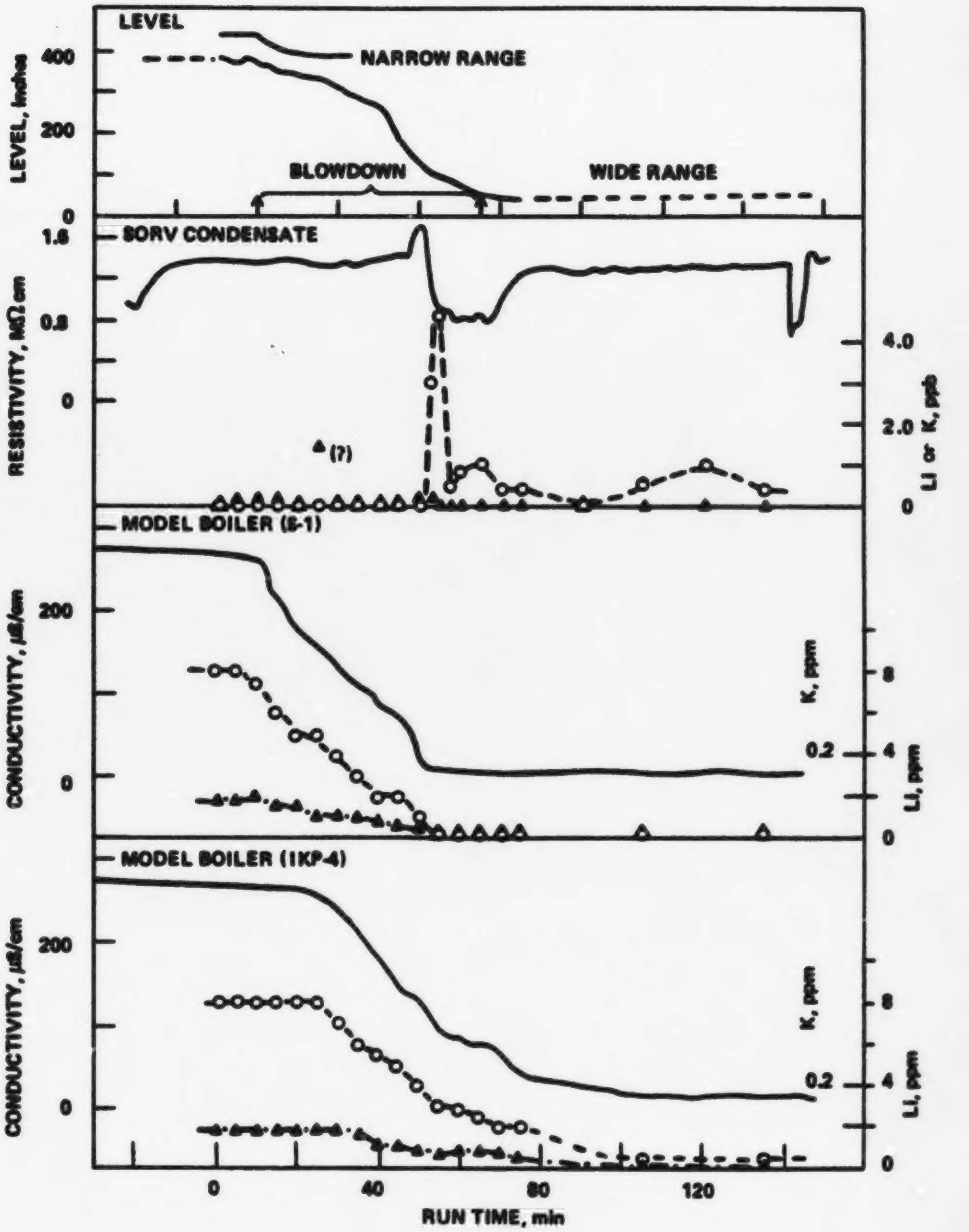

Figure 5-473. Variation in Tracer Concentrations: Blowdown Phase, Test No. 15 (T-2050)

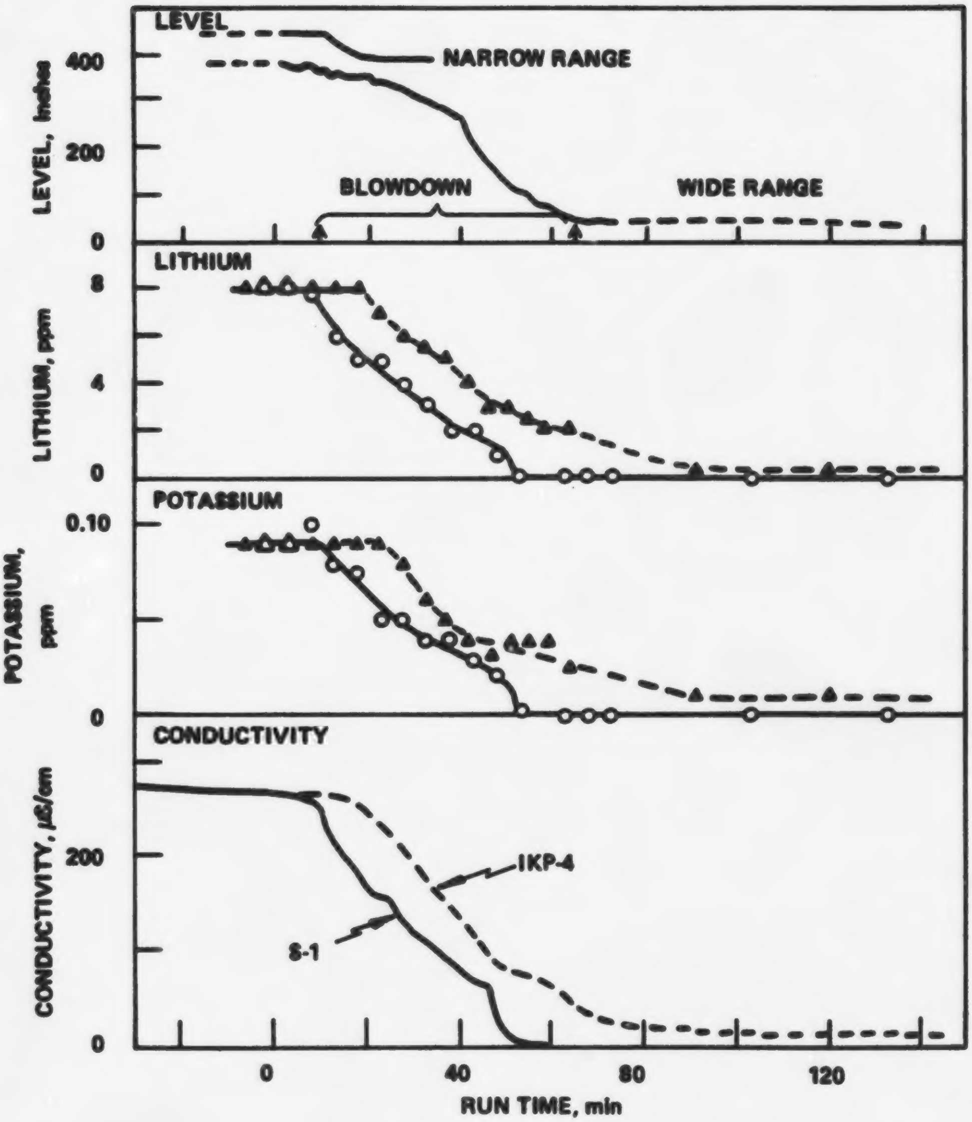

Figure 5-474. Comparison Between S-1 (○) and IKP-4 (▲) Results After Correcting for Sample Line Delays: Blowdown Phase Test No. 15 (T-2050)

448

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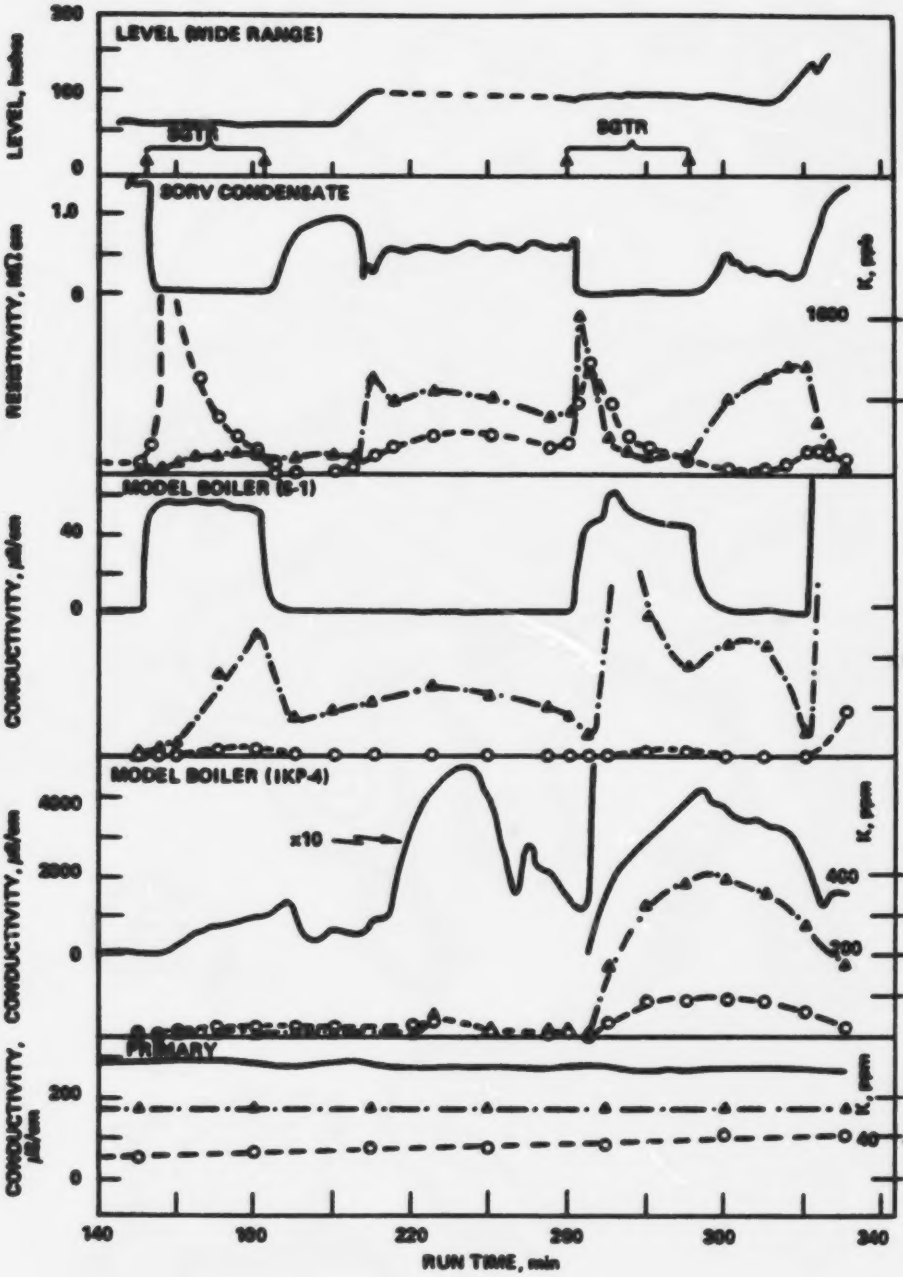

Figure 5-475. Variation in Tracer Concentrations: SGTRs at 60 and 100 in., Test No. 15 (T-2051 and T-2052)

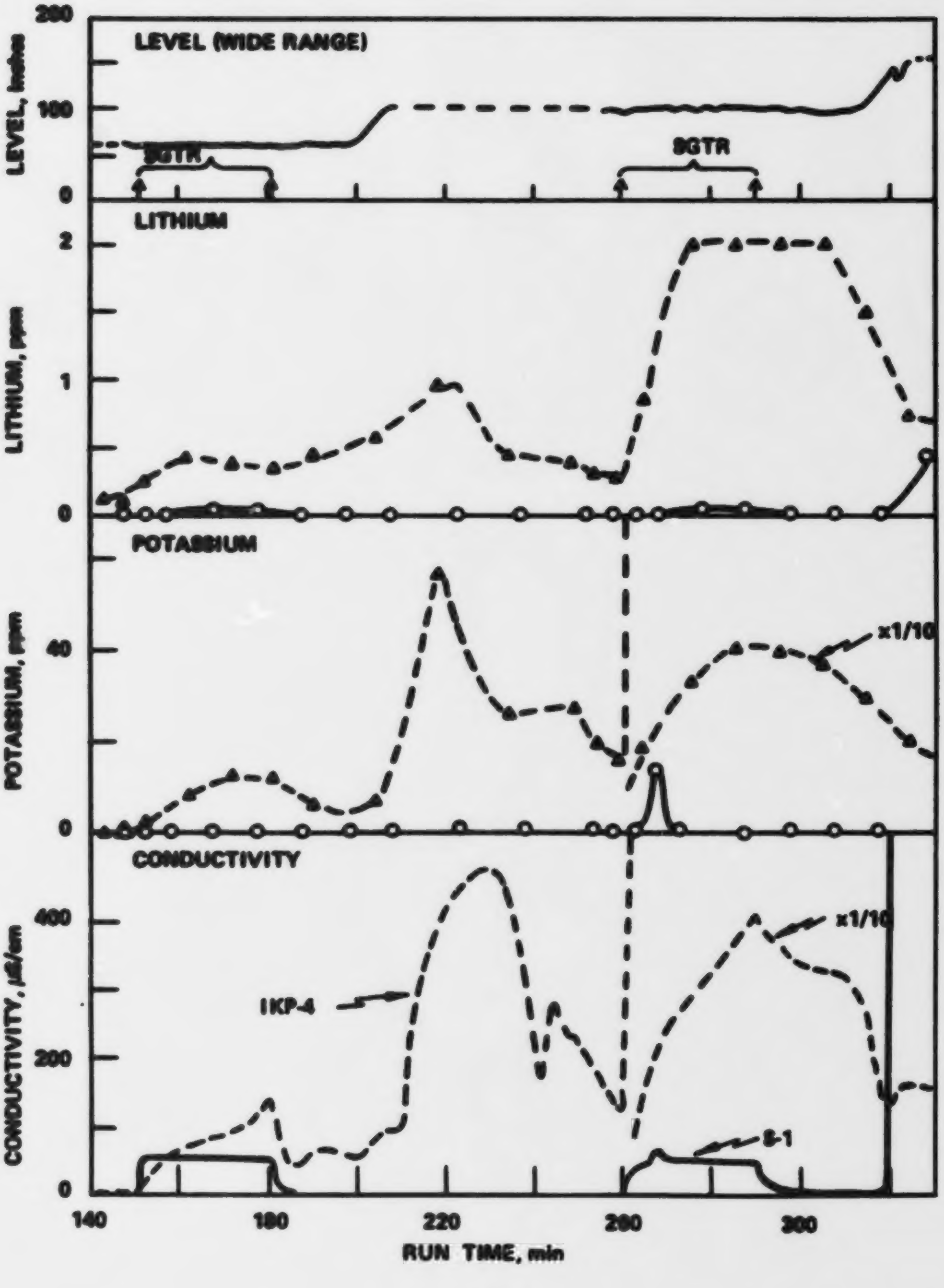

Figure 5-476. Comparison Between S-1 (○) and IKP-4 (▲) Results After Correcting for Sample Line Delays: SGTRs at 60 and 100 in., Test No. 15 (T-2051 and T-2052)

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450

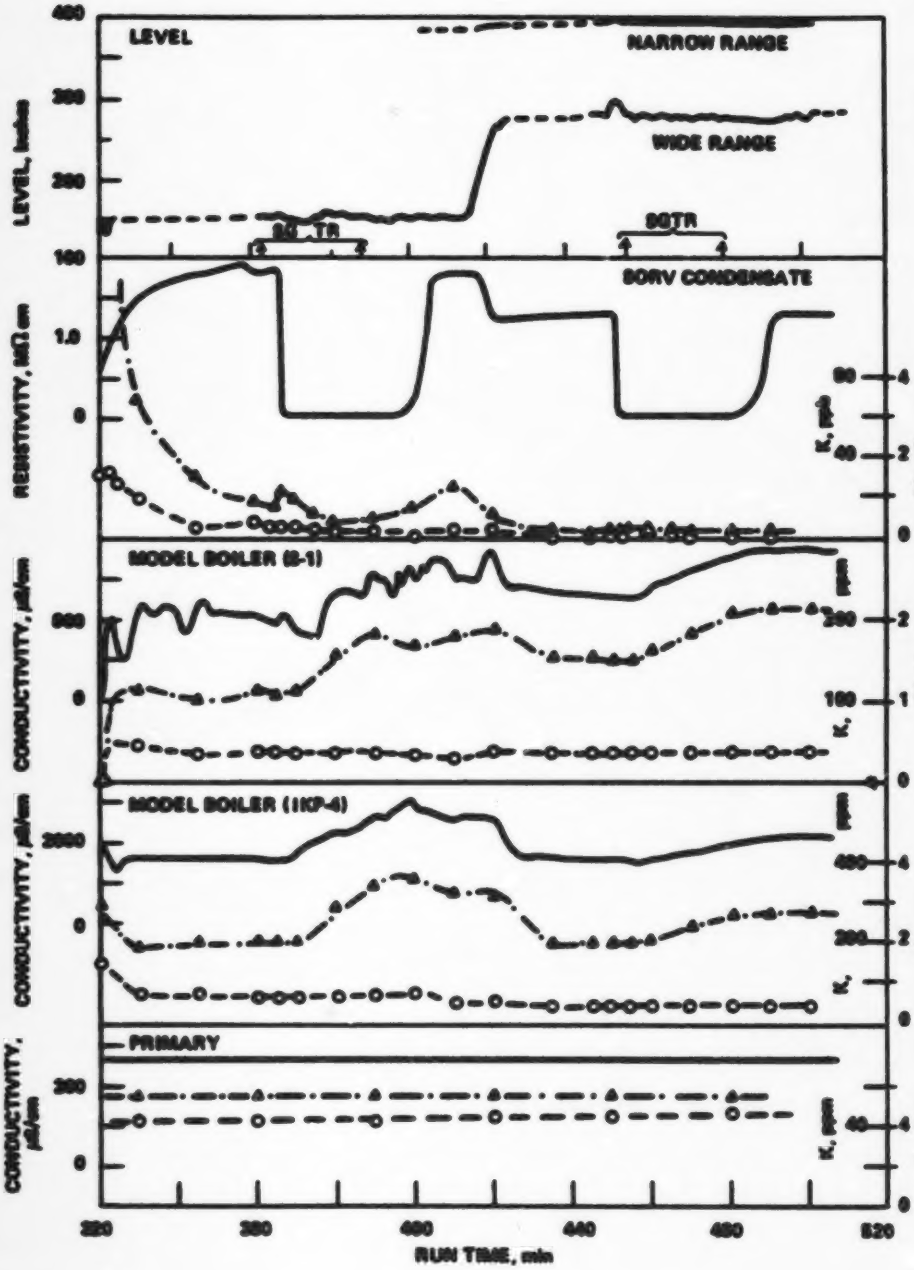

Figure 5-477. Variation in Tracer Concentrations: SGTRs at 160 and 285 in., Test No. 15 (T-2053 and T-2054)

451

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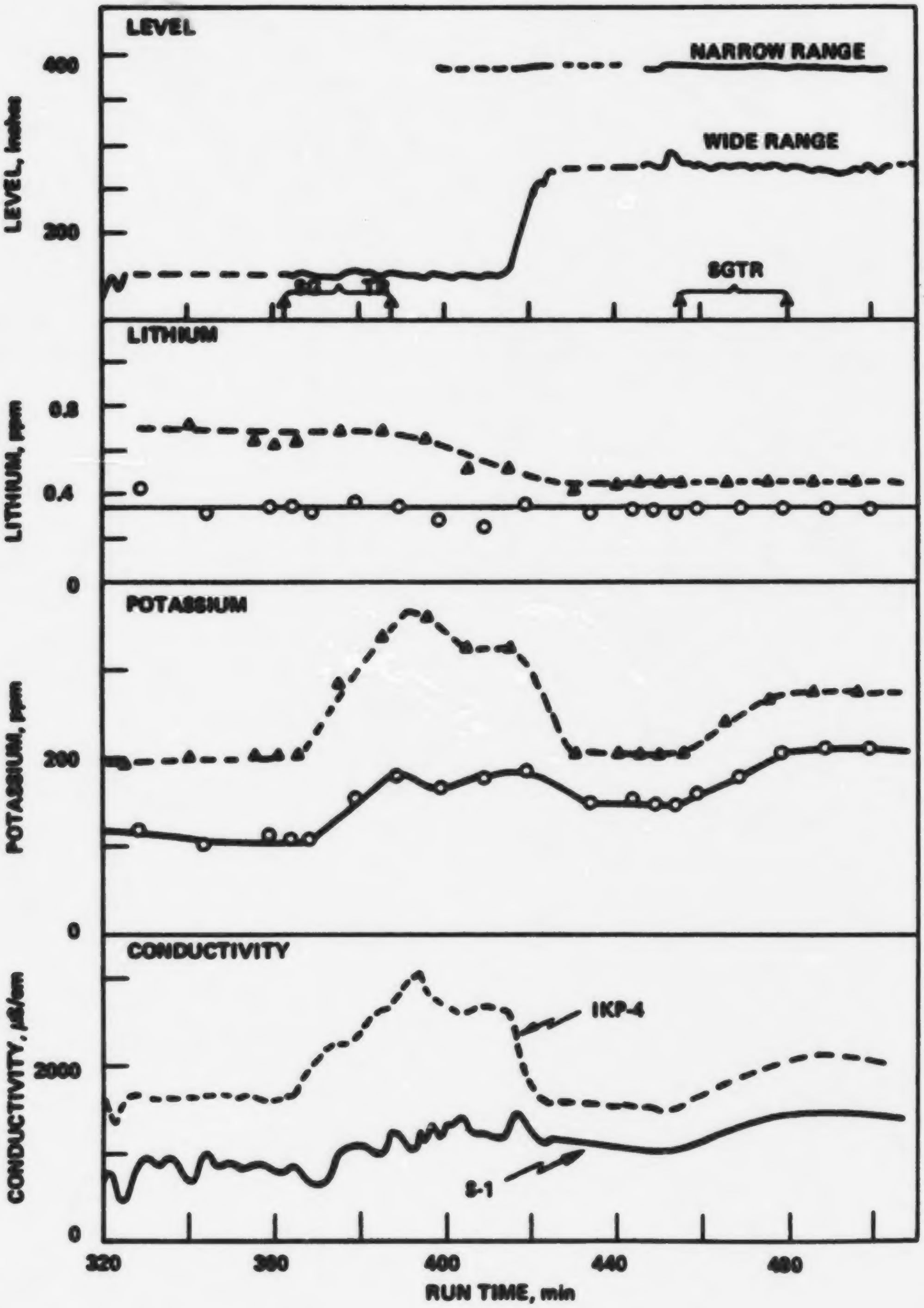

Figure 5-478. Comparison Between S-1 (○) and IKP-4 (▲) Results After Correcting for Sample Line Delays: SGTRs at 160 and 285 in., Test No. 15 (T-2053 and T-2054)

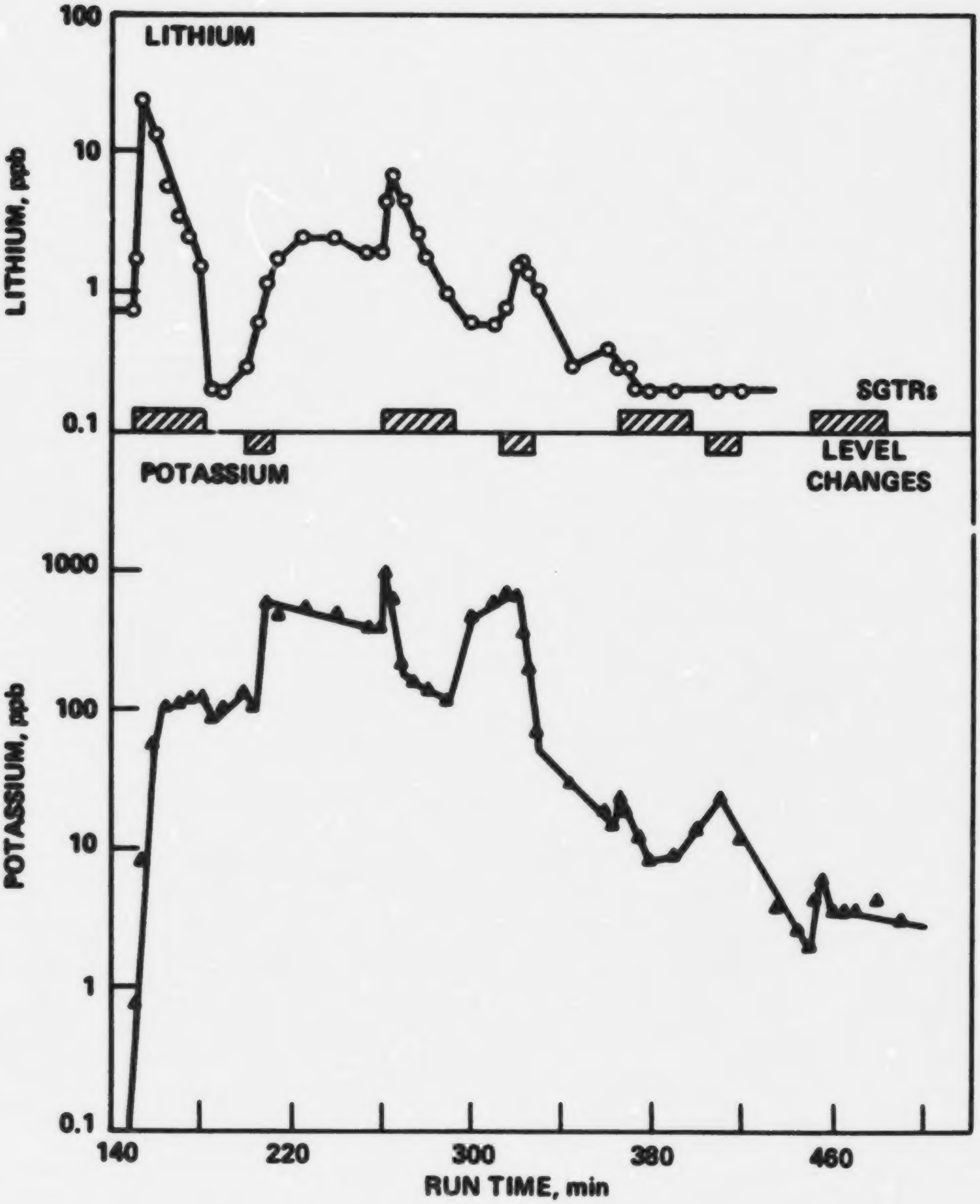

Figure 5-479. Variation in SORV Tracer Concentrations After Correcting for Sample Line Delays: Test No. 15 (T-2050 to T-2054)

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453

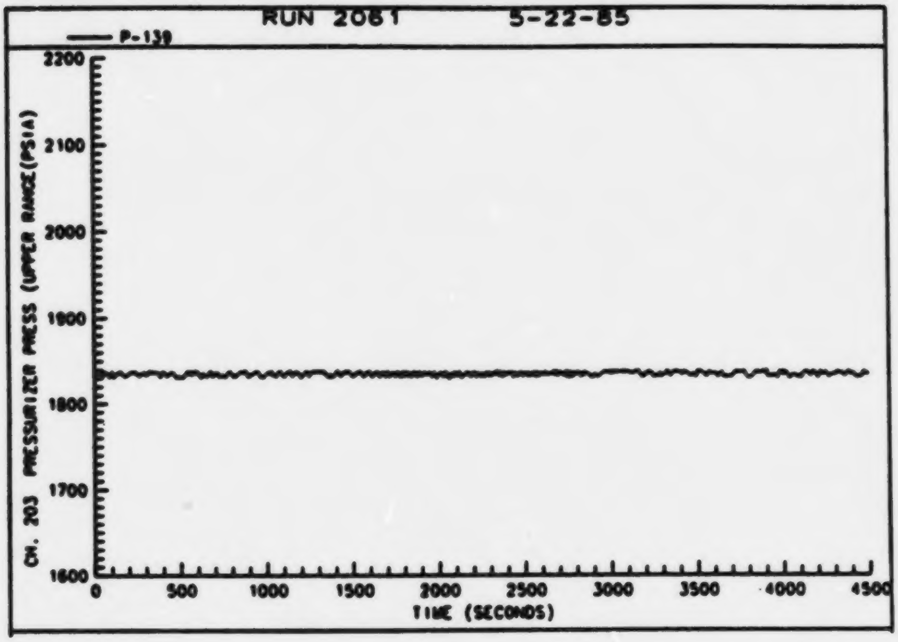

Figure 5-480. Primary System (Pressurizer) Pressure (P-139): Test No. 16 (T-2061)

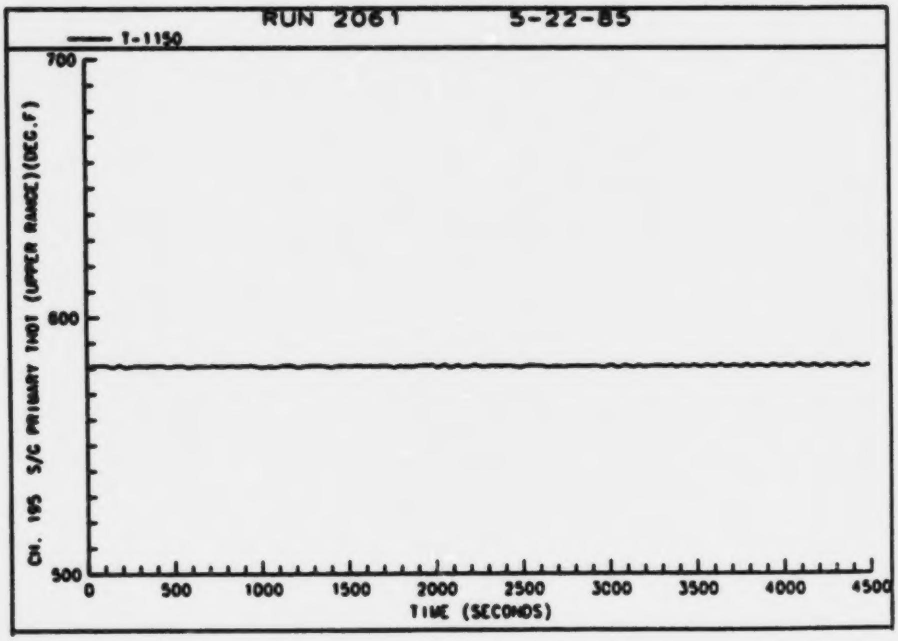

Figure 5-481. Primary Fluid T_{hot} (T-1150): Test No. 16 (T-2061)

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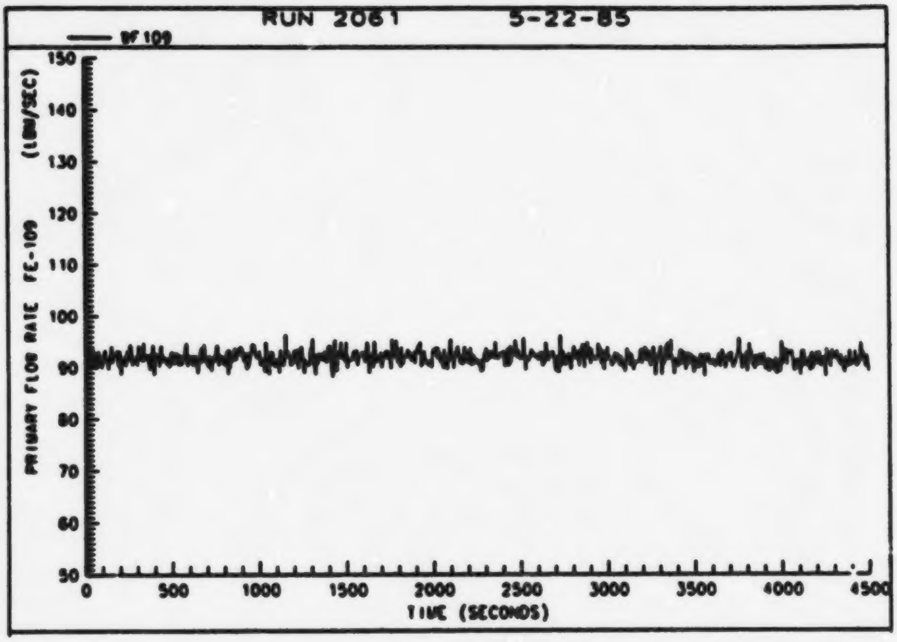

Figure 5-482. Primary Fluid Flow Rate (WF-109): Test No. 16 (T-2061)

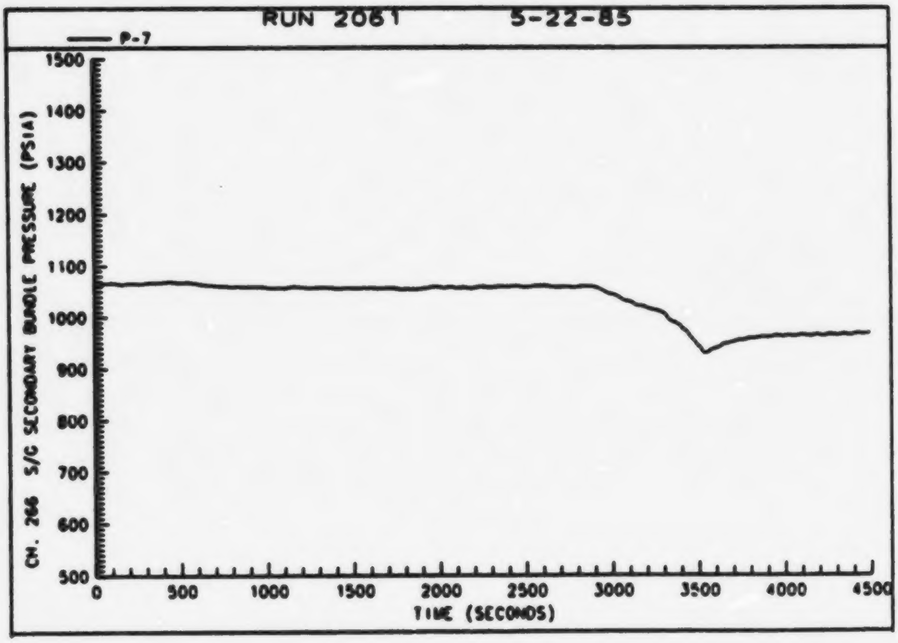

Figure 5-483. Secondary Side Pressure (P-7): Test No. 16 (T-2061)

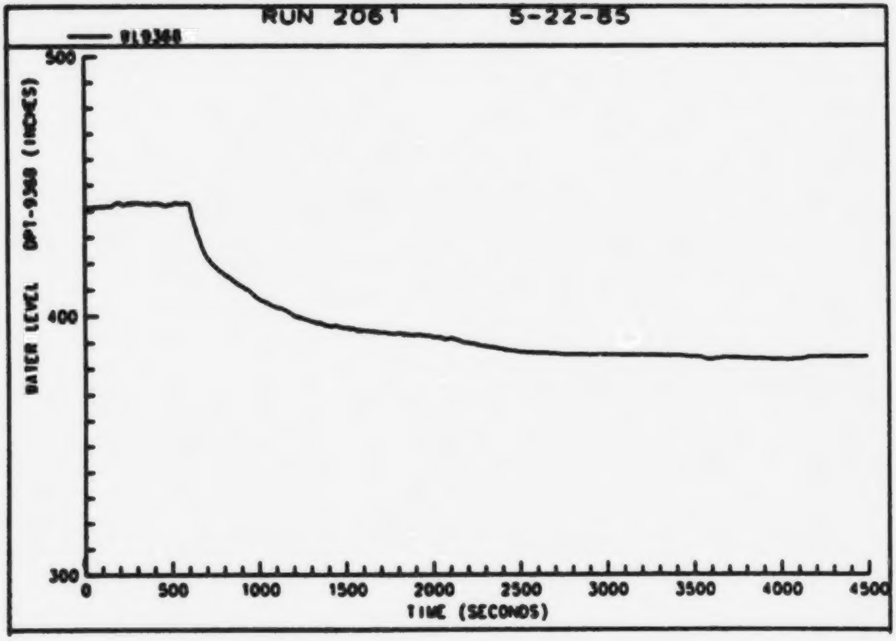

Figure 5-484. Downcomer Water Level - Narrow Range (WL-9368): Test No. 16 (T-2061)

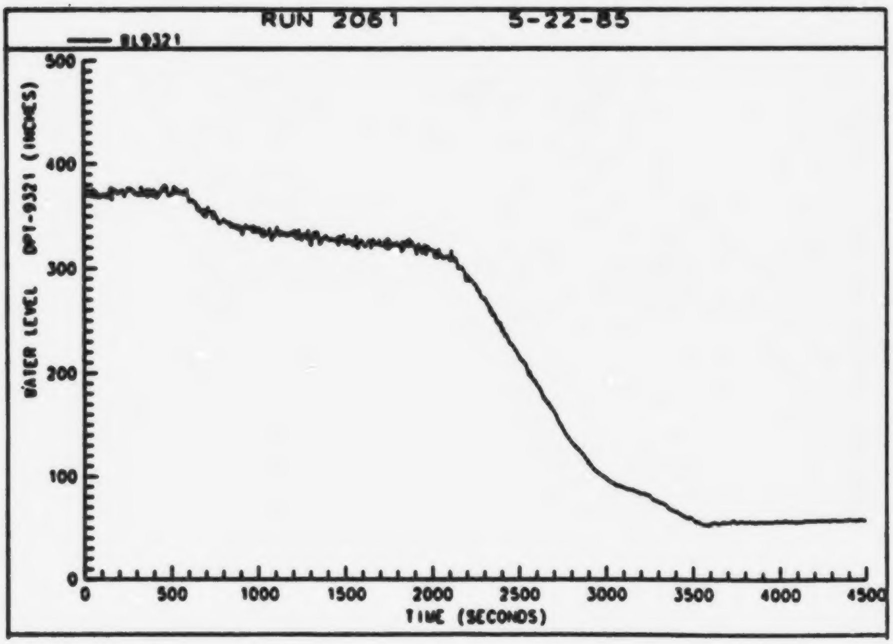

Figure 5-485. Downcomer Water Level - Wide Range (WL-9321): Test No. 15 (T-2061)

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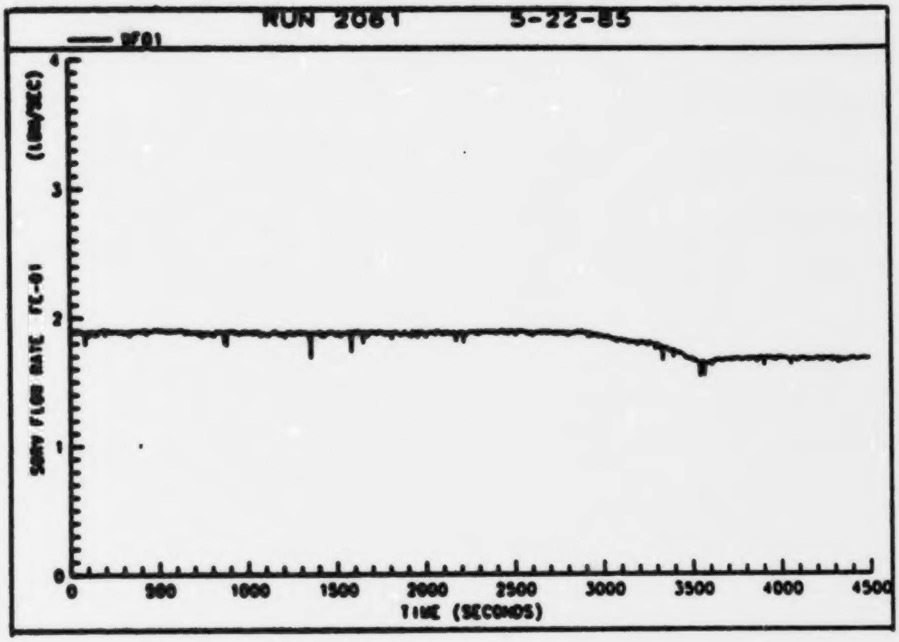

Figure 5-486. SORV Flow Rate (WF-01):
Test No. 16 (T-2061)

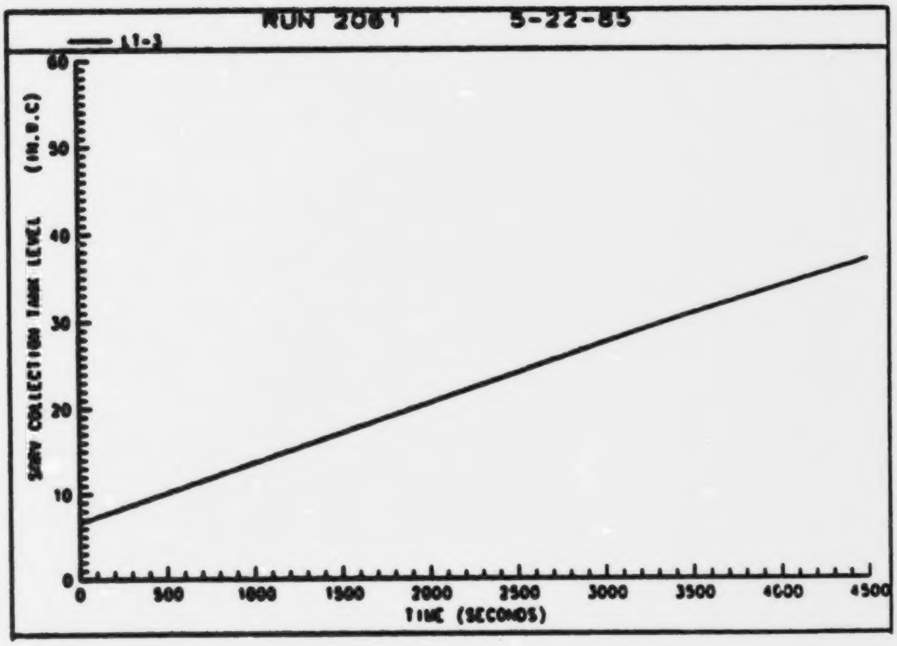

Figure 5-487. SORV Tank Level (LT-3):
Test No. 16 (T-2061)

457

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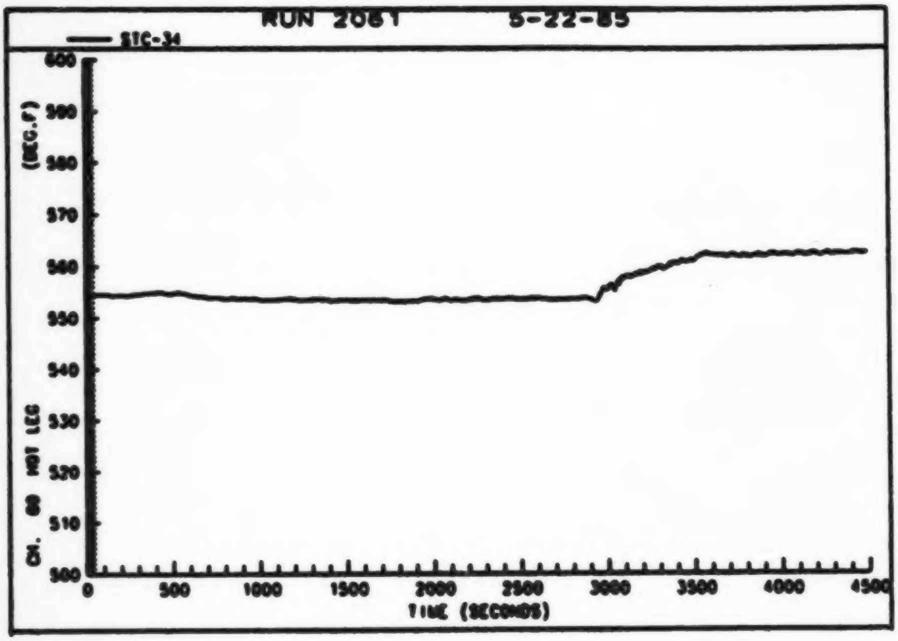

Figure 5-488. Secondary Fluid Temperature (STC-34): Test No. 16 (T-2061)

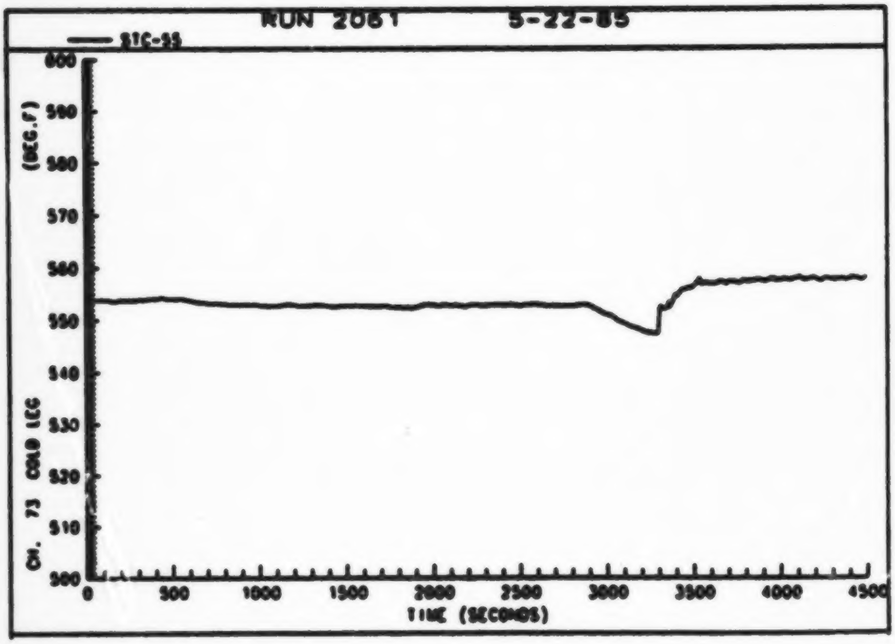

Figure 5-489. Secondary Fluid Temperature (STC-55): Test No. 16 (T-2061)

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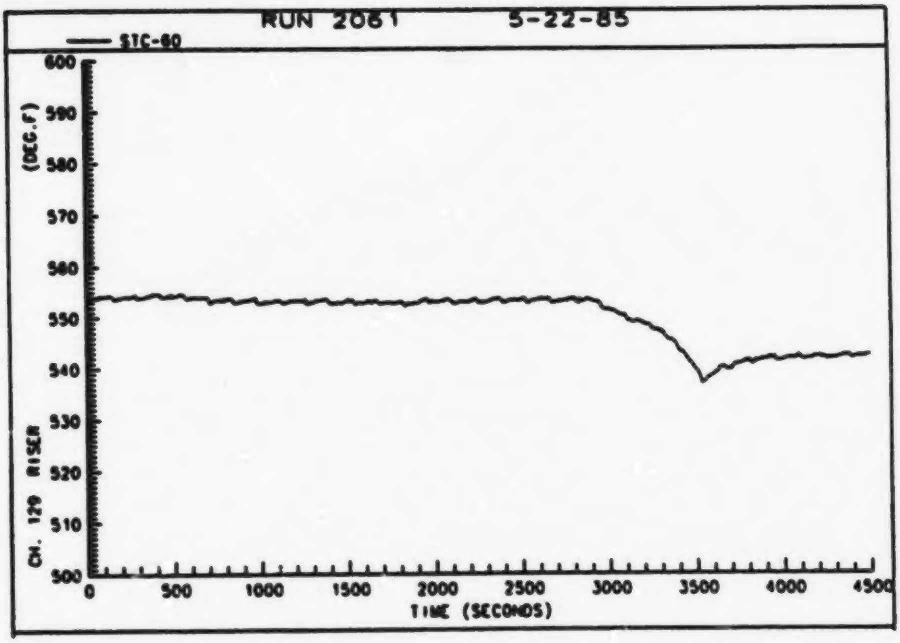

Figure 5-490. Secondary Fluid Temperature (STC-60): Test No. 16 (T-2061)

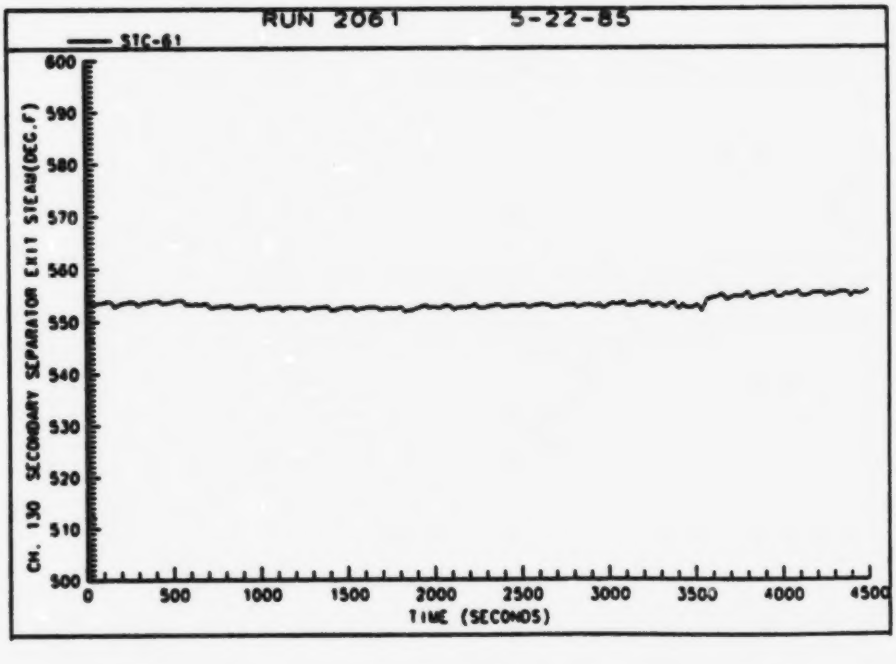

Figure 5-491. Secondary Fluid Temperature (STC-61): Test No. 16 (T-2061)

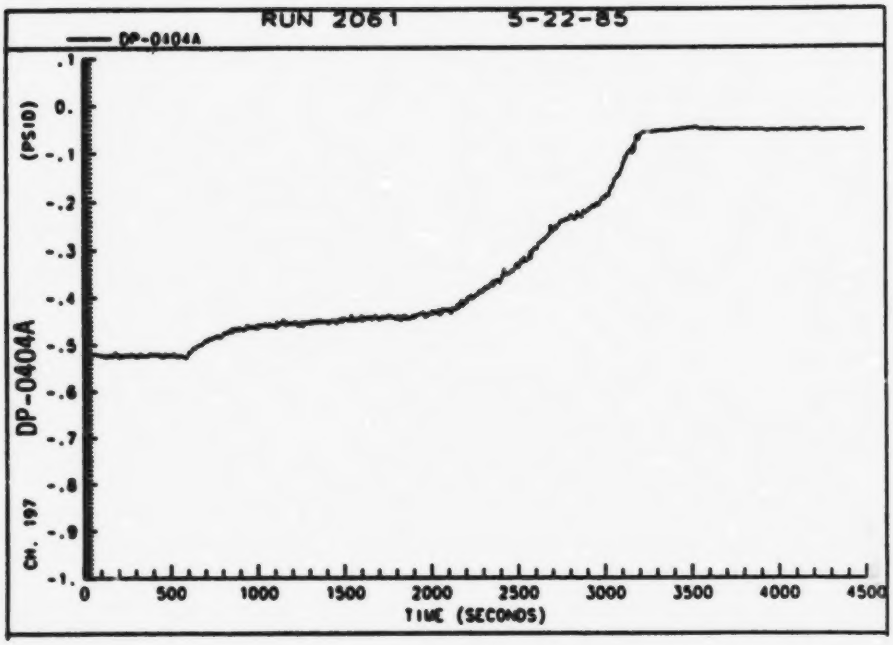

Figure 5-492. Differential Pressure, DP-0404A: Test No. 16 (T-2061)

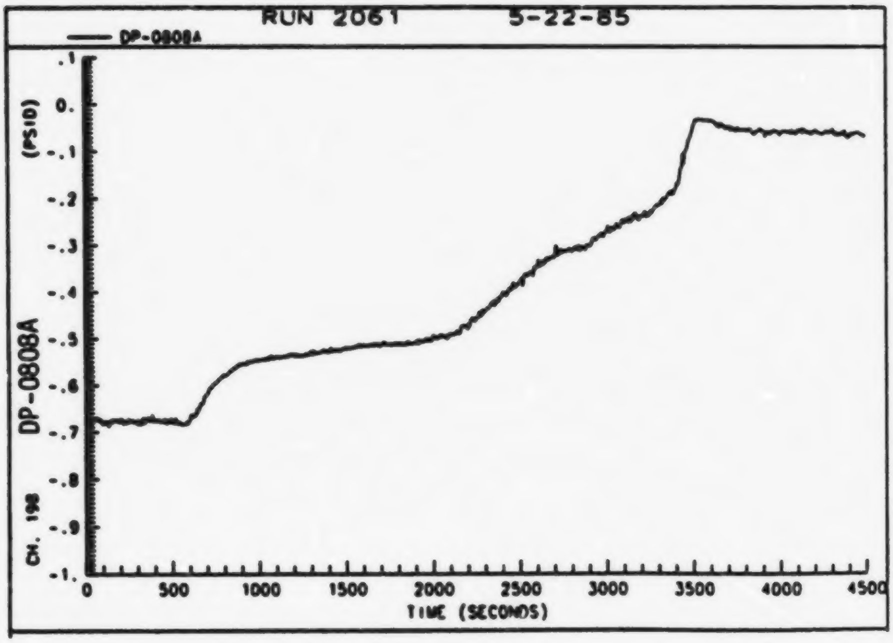

Figure 5-493. Diff[illegible]ntial Pressure, DP-0808A: Test No. 16 (T-2061)

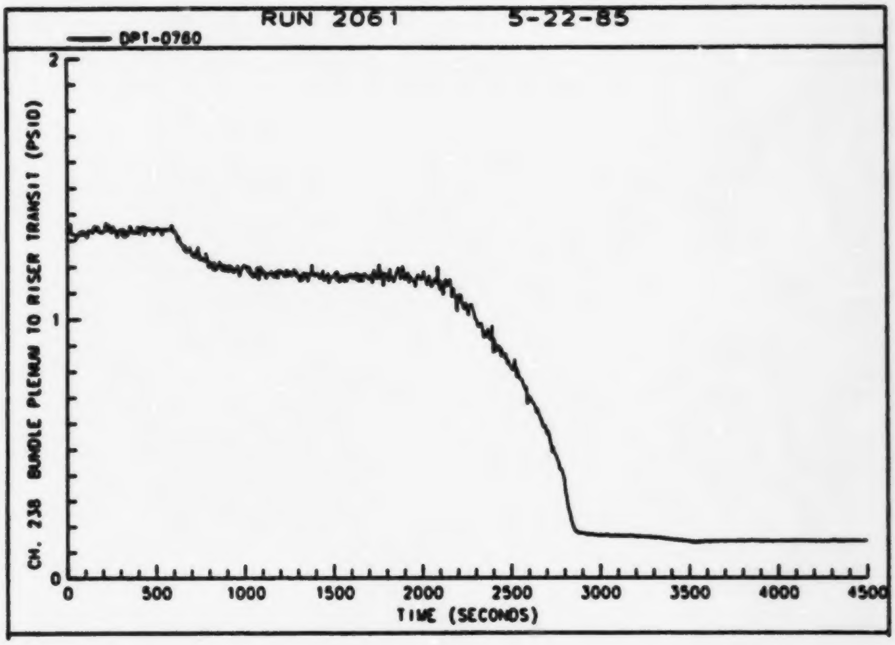

Figure 5-494. Differential Pressure, DP-0760: Test No. 16 (T-2061)

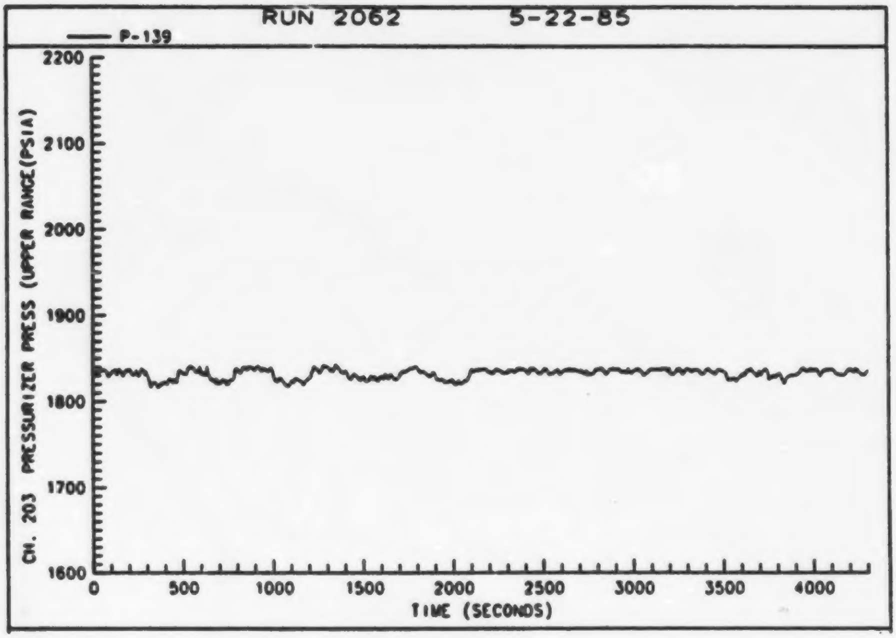

Figure 5-495. Primary System (Pressurizer) Pressure (P-139): Test No. 16 (T-2062)

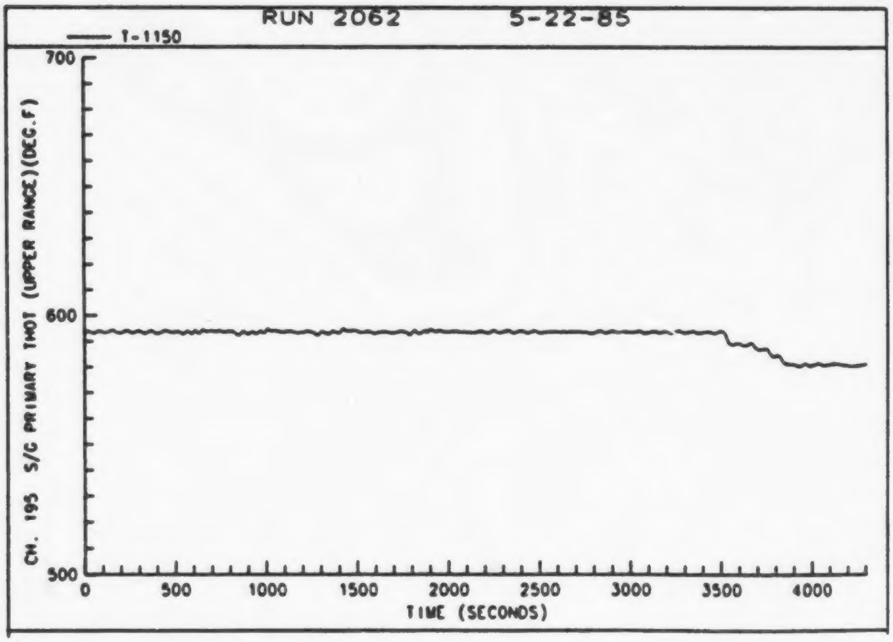

Figure 5-496. Primary Fluid T_{hot} (T-1150): Test No. 16 (T-2062)

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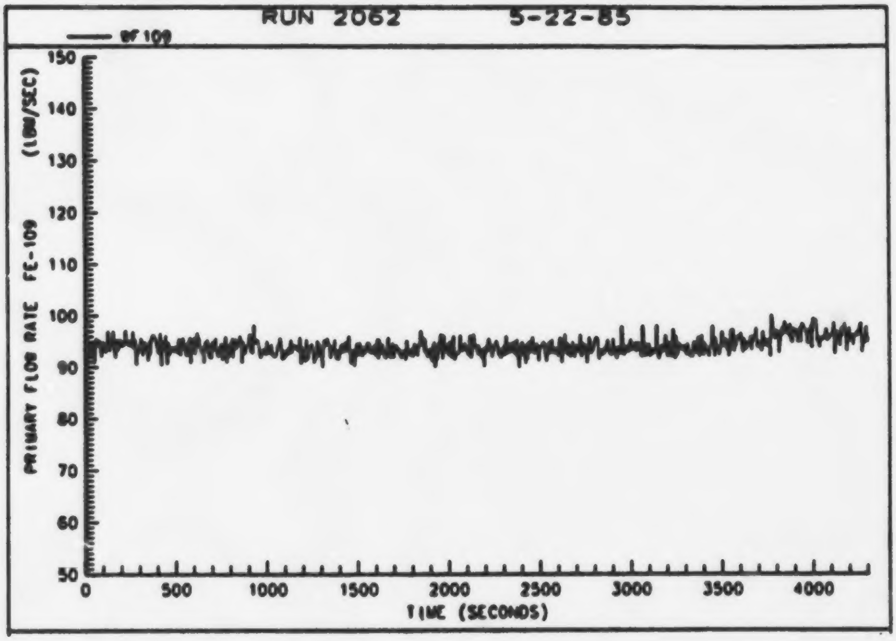

Figure 5-497. Primary Fluid Flow Rate (WF-109): Test No. 16 (T-2062)

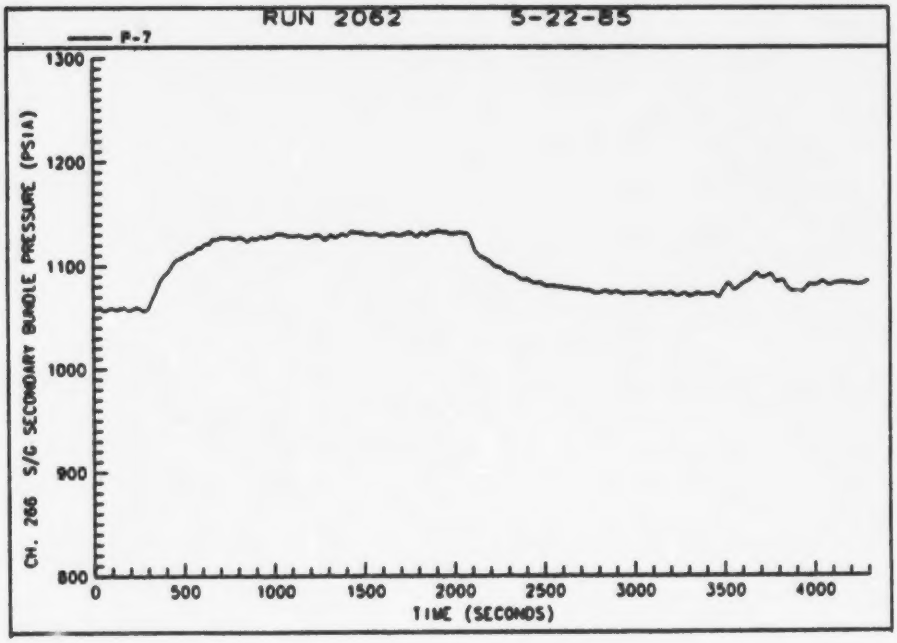

Figure 5-498. Secondary Side Pressure (P-7): Test No. 16 (T-2062)

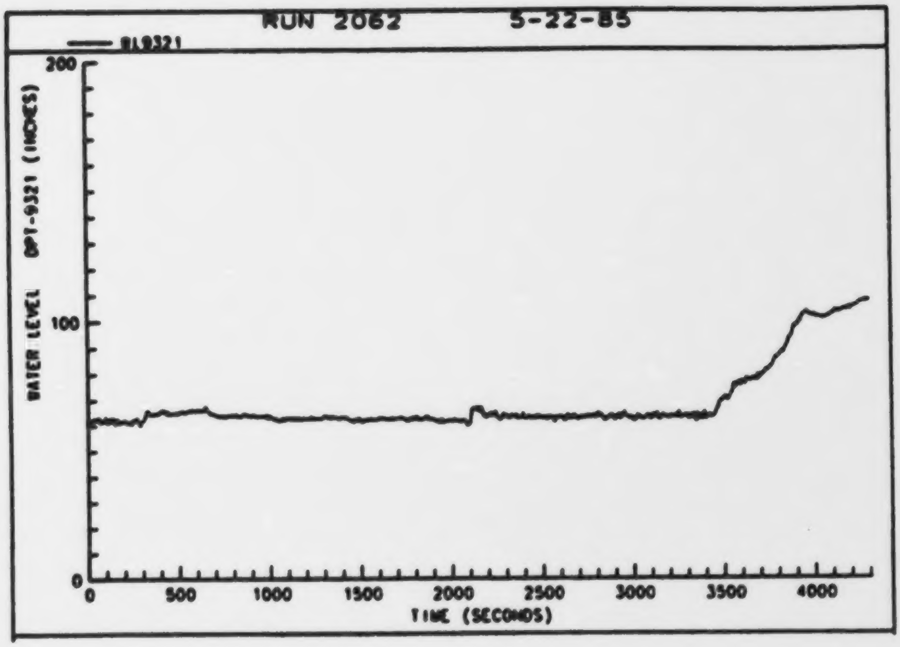

Figure 5-499. Downcomer Water Level - Wide Range (WL-9321): Test No. 16 (T-2062)

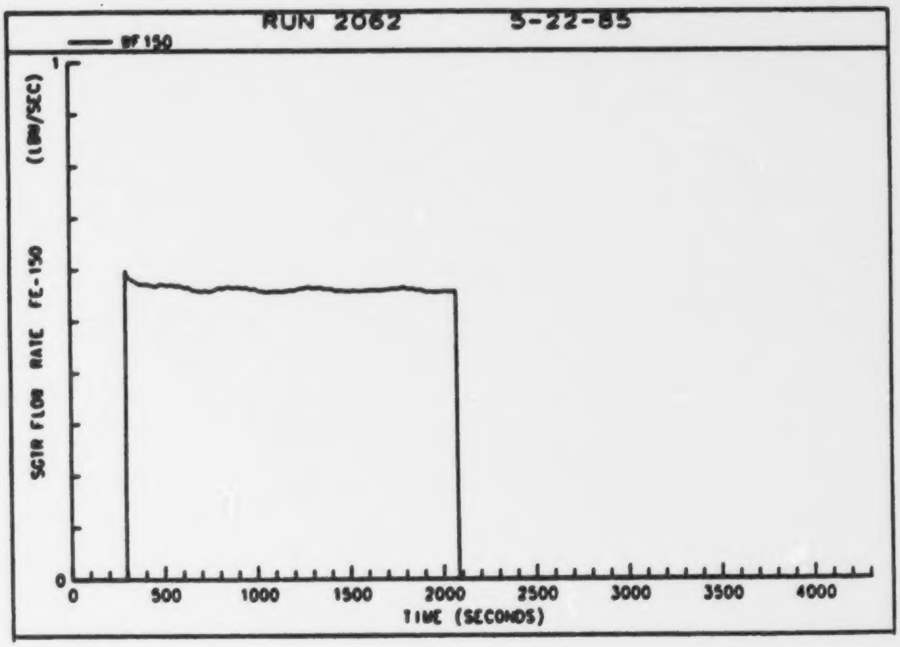

Figure 5-500. SGTR Flow Rate (WF-150): Test No. 16 (T-2062)

464

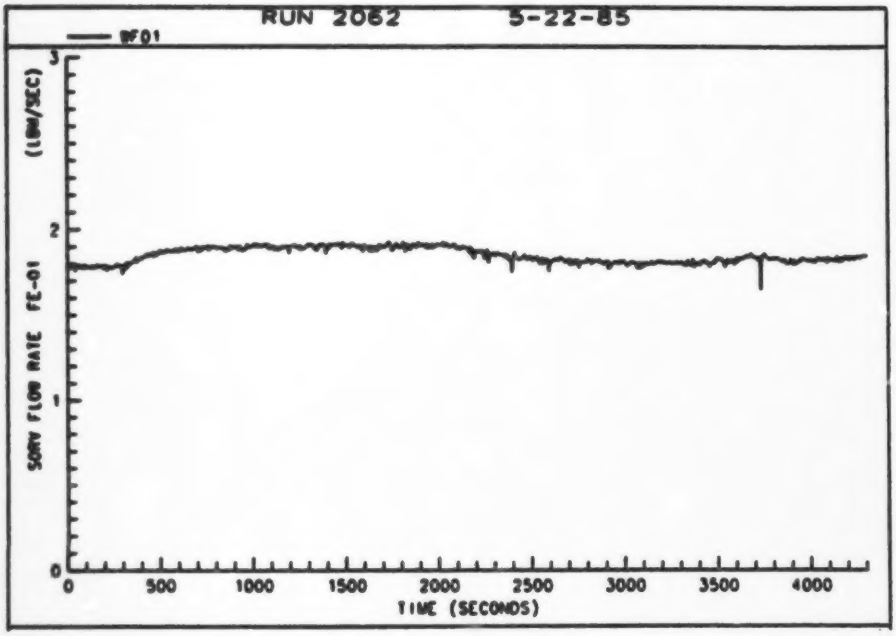

Figure 5-501. SORV Flow Rate (WF-01): Test No. 16 (T-2062)

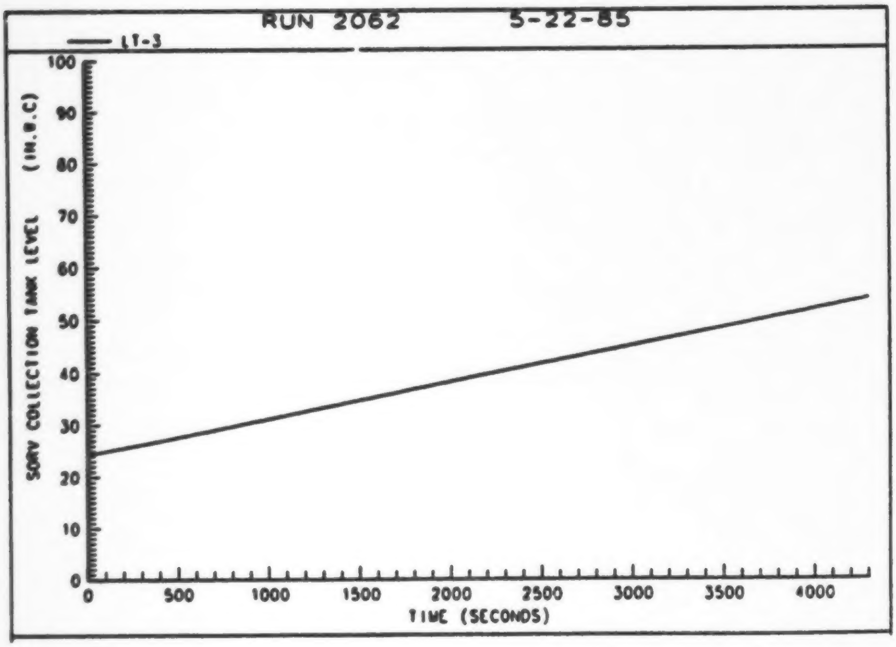

Figure 5-502. SORV Tank Level (LT-3): Test No. 16 (T-2062)

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465

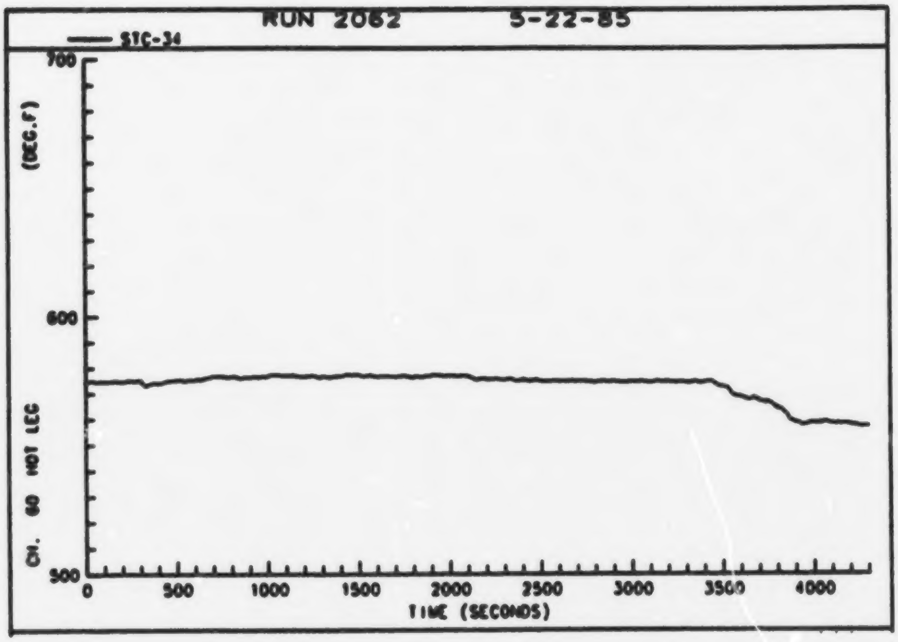

Figure 5-503. Secondary Fluid Temperature (STC-34): Test No. 16 (T-2062)

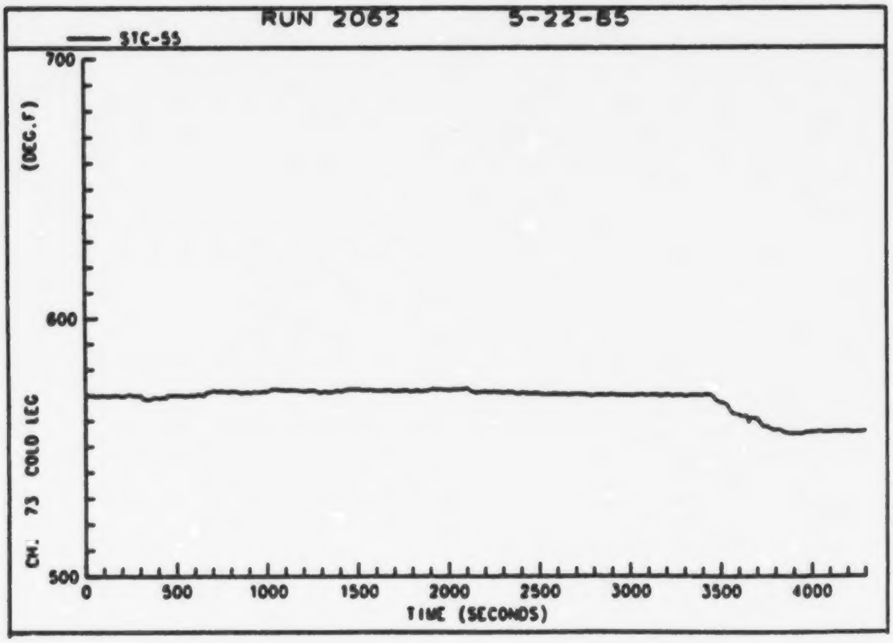

Figure 5-504. Secondary Fluid Temperature (STC-55): Test No. 16 (T-2062)

466

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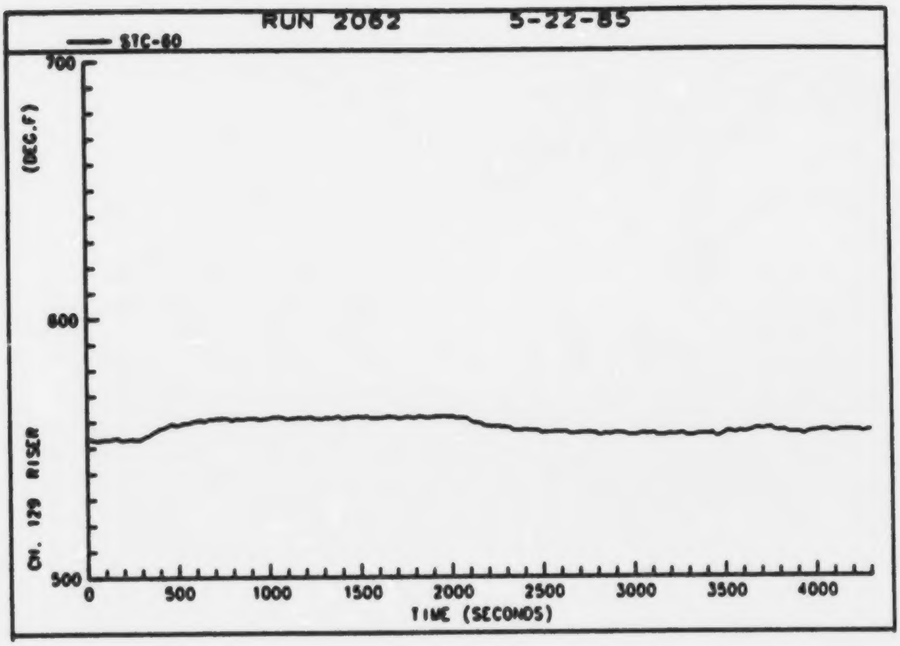

Figure 5-505. Secondary Fluid Temperature (STC-60): Test No. 16 (T-2062)

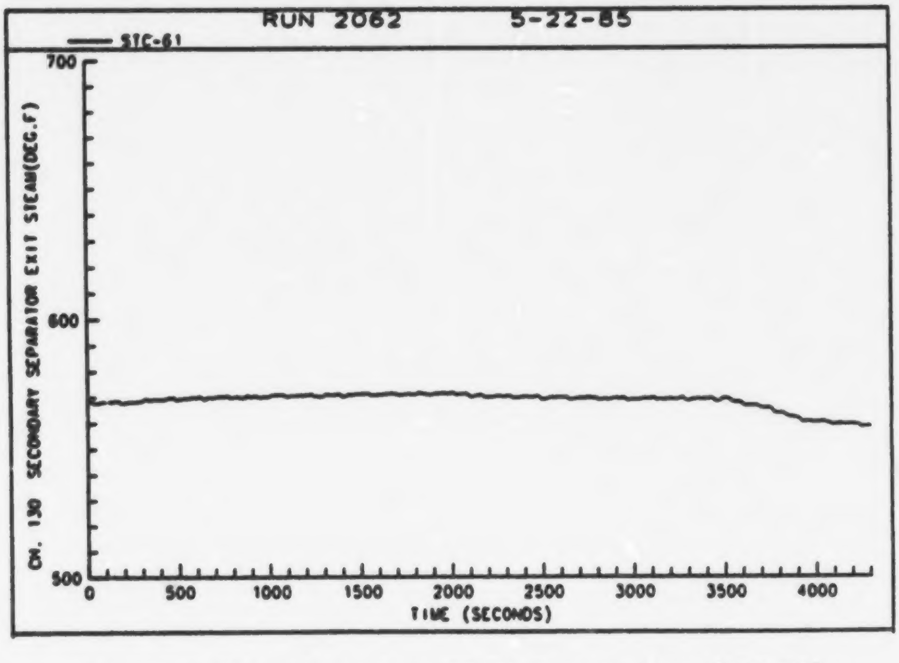

Figure 5-506. Secondary Fluid Temperature (STC-61): Test No. 16 (T-2062)

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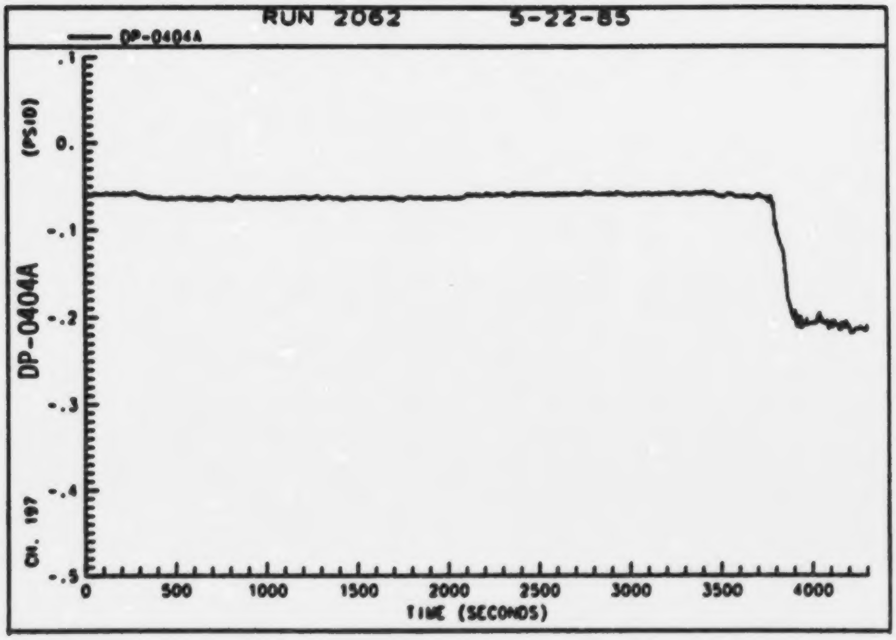

Figure 5-507. Differential Pressure, DP-0404A: Test No. 16 (T-2062)

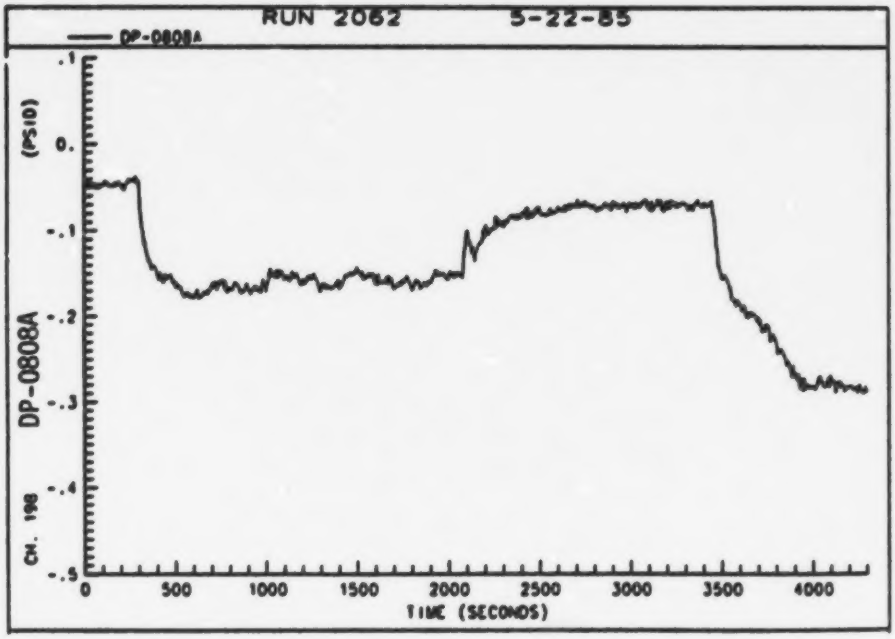

Figure 5-508. Differential Pressure, DP-0808A: Test No. 16 (T-2062)

468

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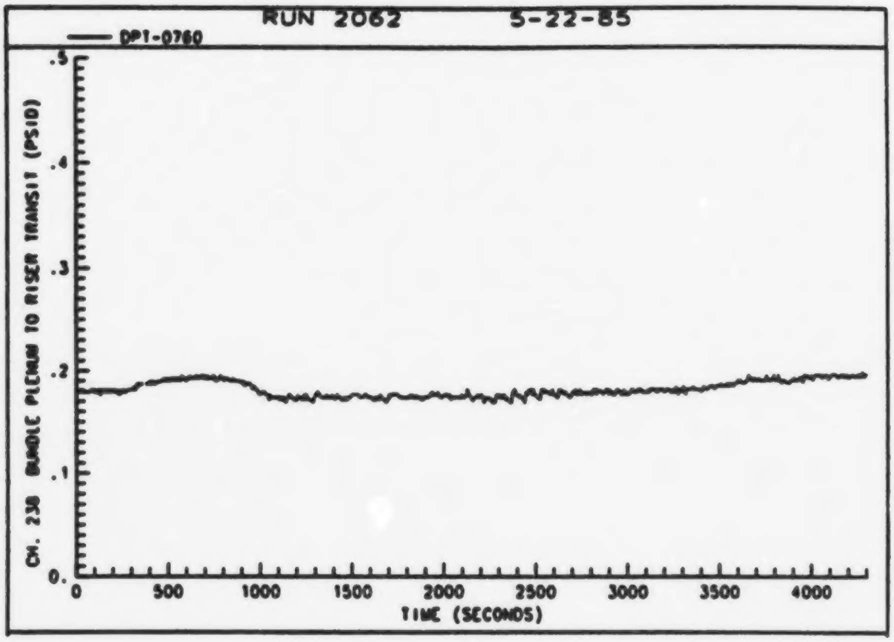

Figure 5-509. Differential Pressure, DP-0760: Test No. 16 (T-2062)

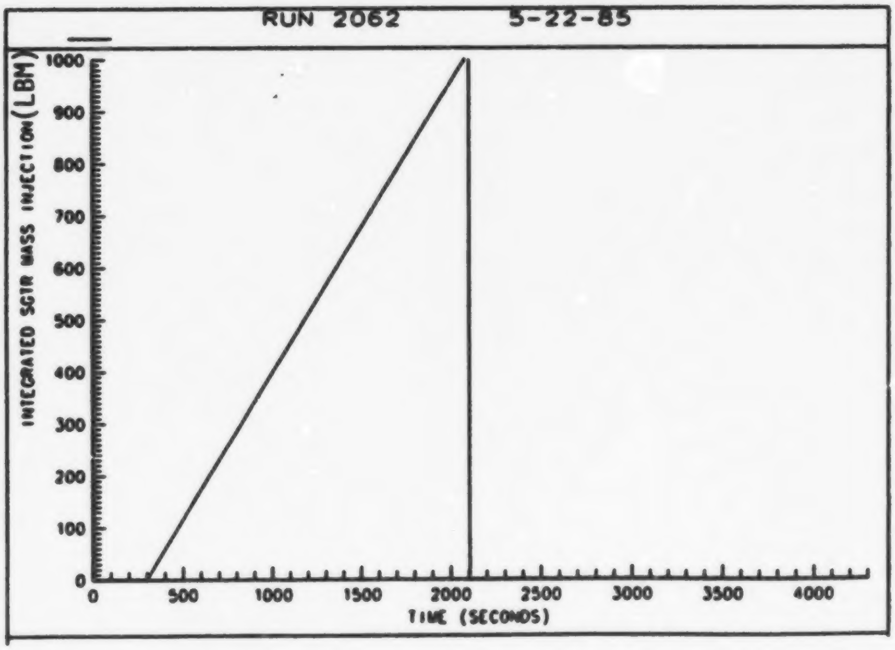

Figure 5-510. Integrated SGRR Flow: Test No. 16 (T-2062)

469

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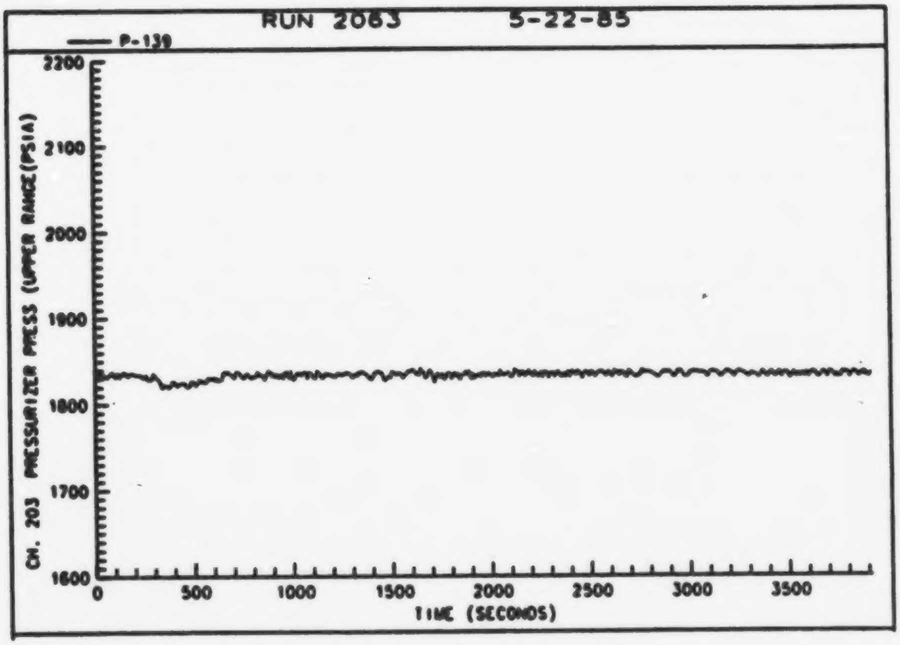

Figure 5-511. Primary System (Pressurizer) Pressure (P-139): Test No. 16 (T-2063)

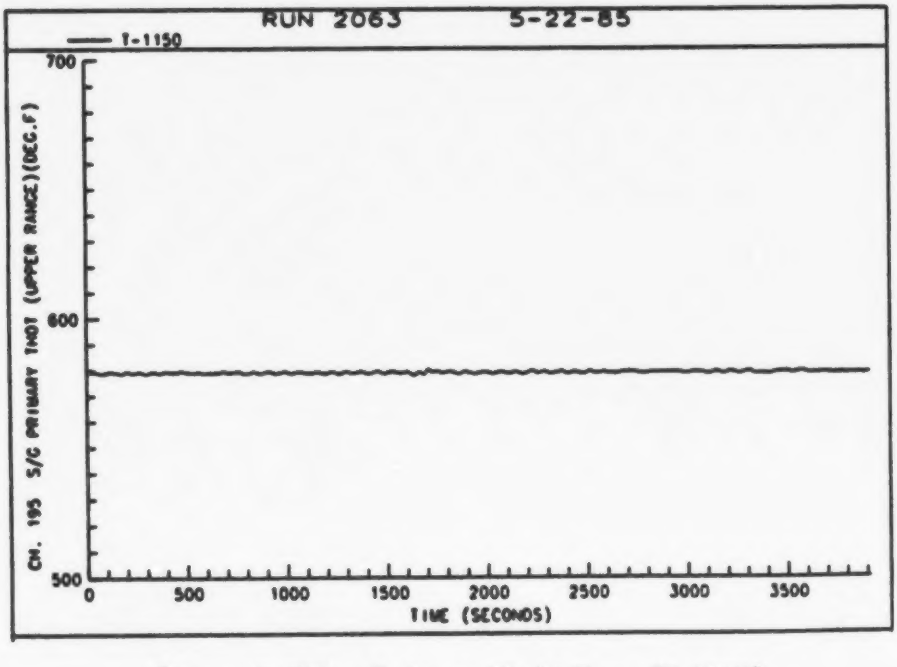

Figure 5-512. Primary Fluid T_{hot} (T-1150): Test No. 16 (T-2063)

470

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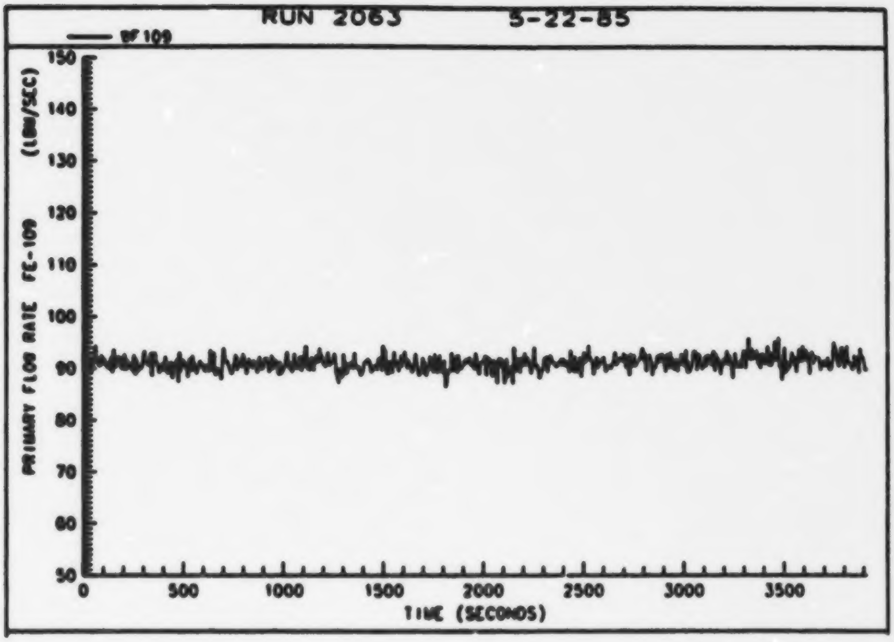

Figure 5-513. Primary Fluid Flow Rate (WF-109):
Test No. 16 (T-2063)

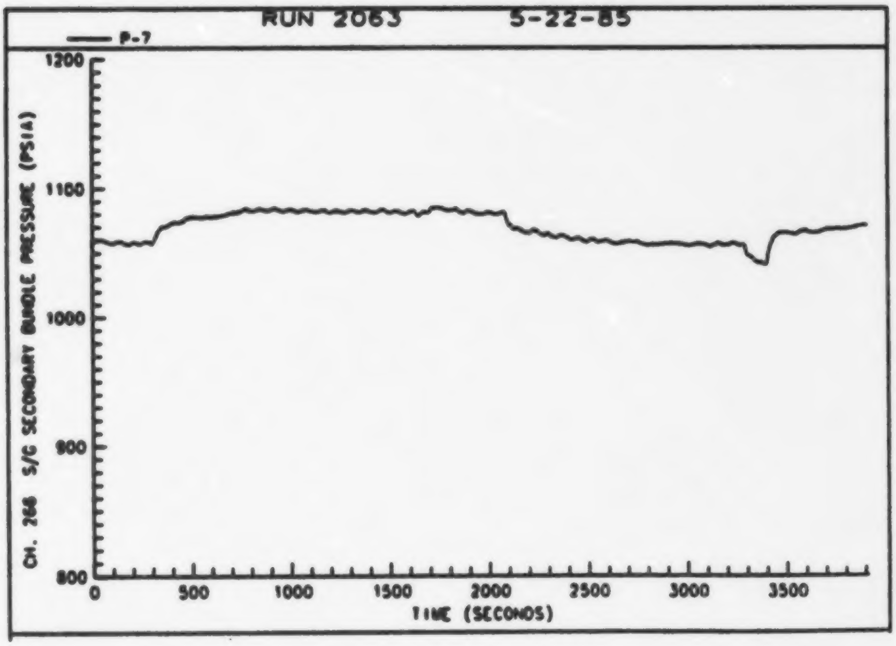

Figure 5-514. Secondary Side Pressure (P-7):
Test No. 16 (T-2063)

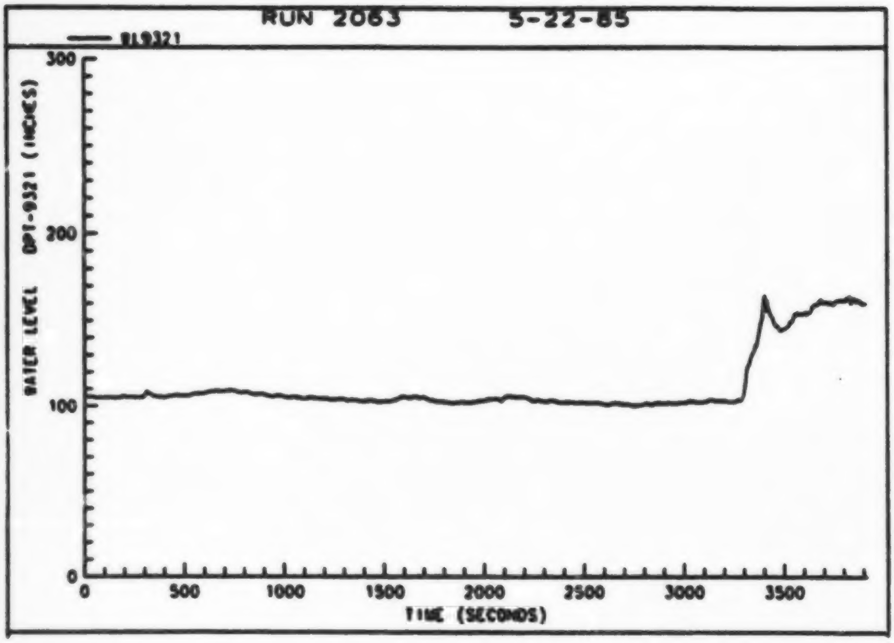

Figure 5-515. Downcomer Water Level - Wide Range (WL-9321): Test No. 16 (T-2063)

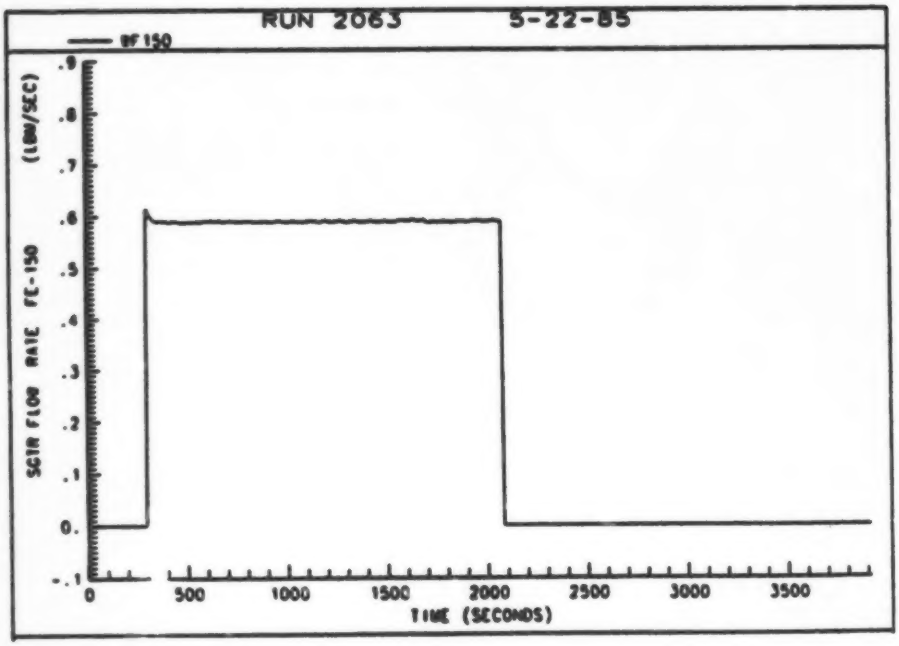

Figure 5-516. SGTR Flow Rate (WF-150): Test No. 16 (T-2063)

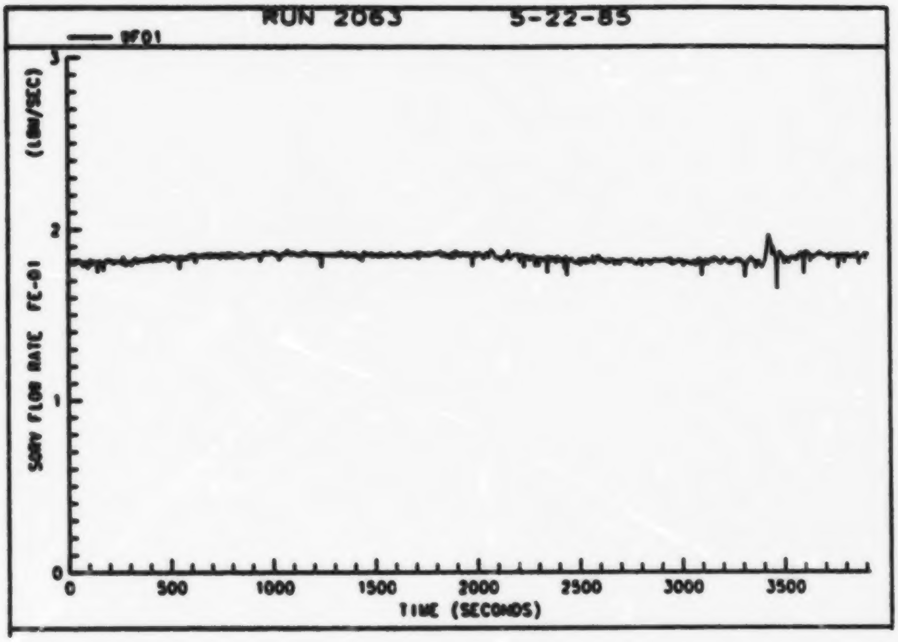

Figure 5-517. SORV Flow Rate (WF-01):
Test No. 16 (T-2063)

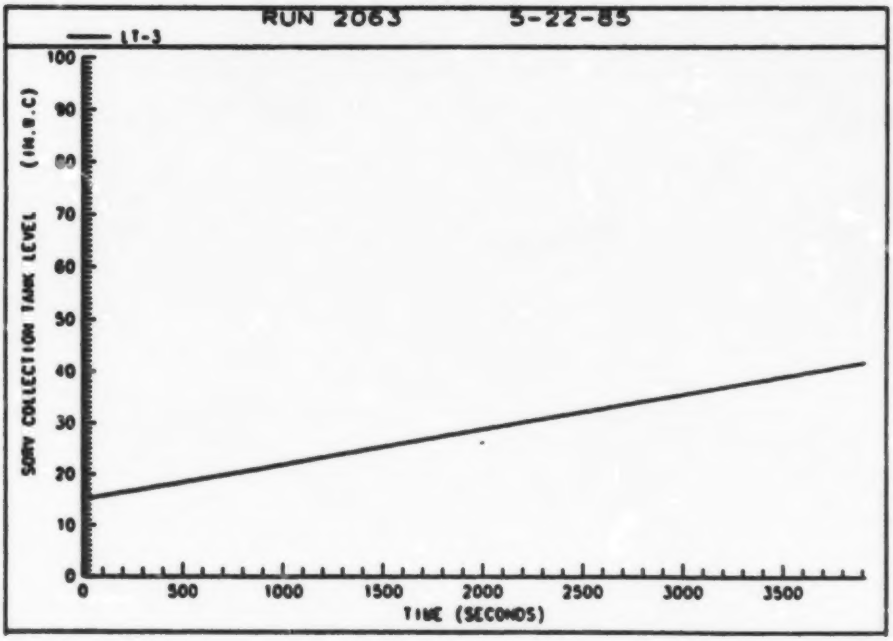

Figure 5-518. SORV Tank Level (LT-3):
Test No. 16 (T-2063)

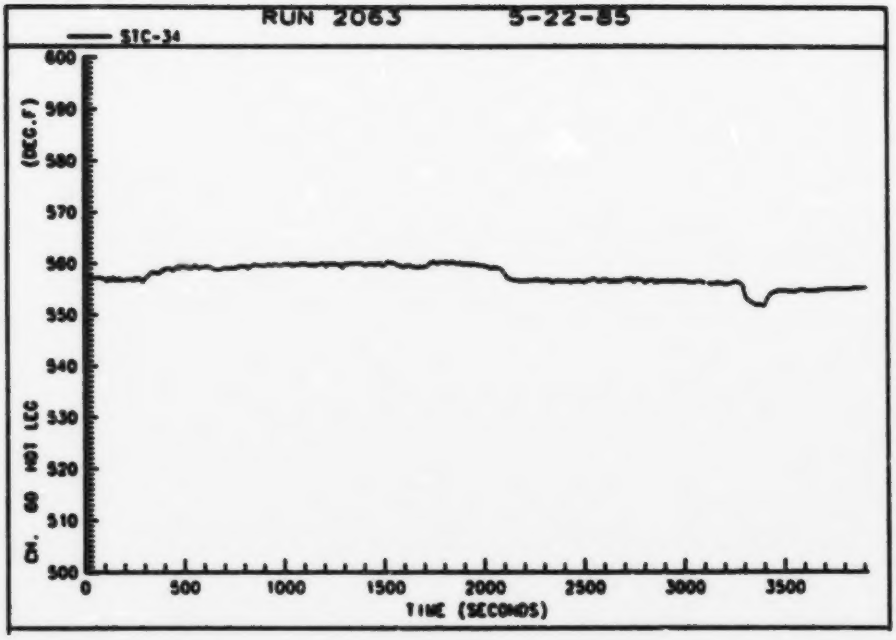

Figure 5-519. Secondary Fluid Temperature (STC-34): Test No. 16 (T-2063)

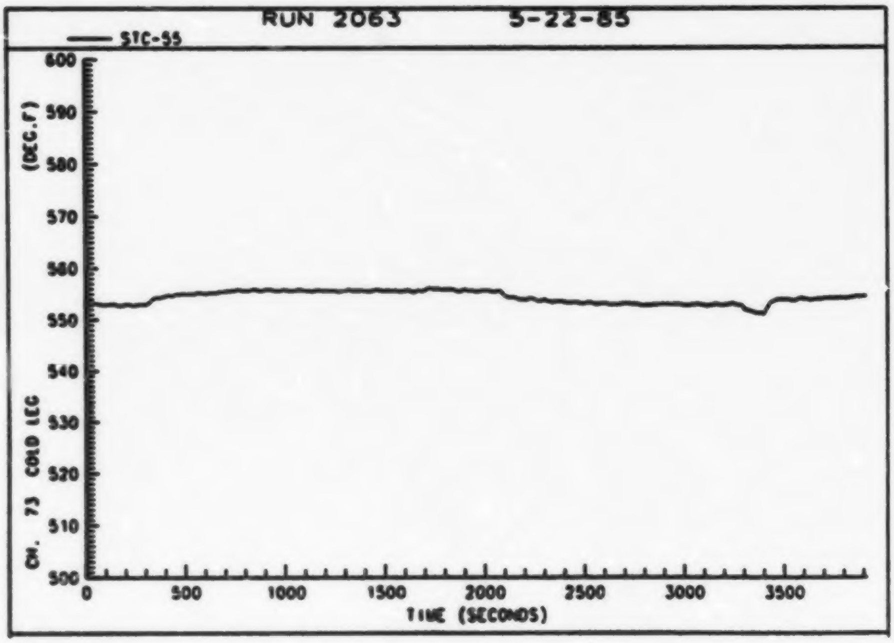

Figure 5-520. Secondary Fluid Temperature (STC-55): Test No. 16 (T-2063)

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474

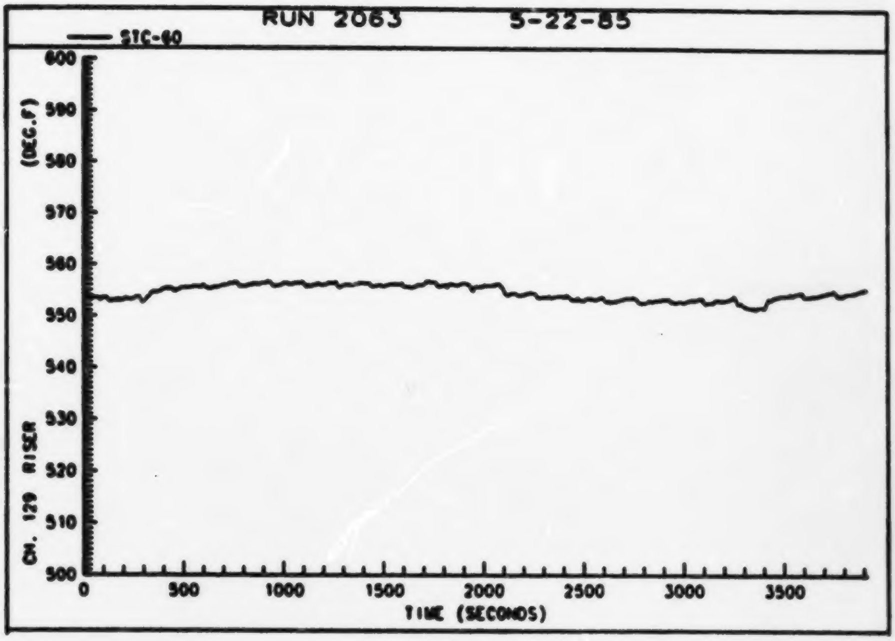

Figure 5-521. Secondary Fluid Temperature (STC-60): TEst No. 16 (T-2063)

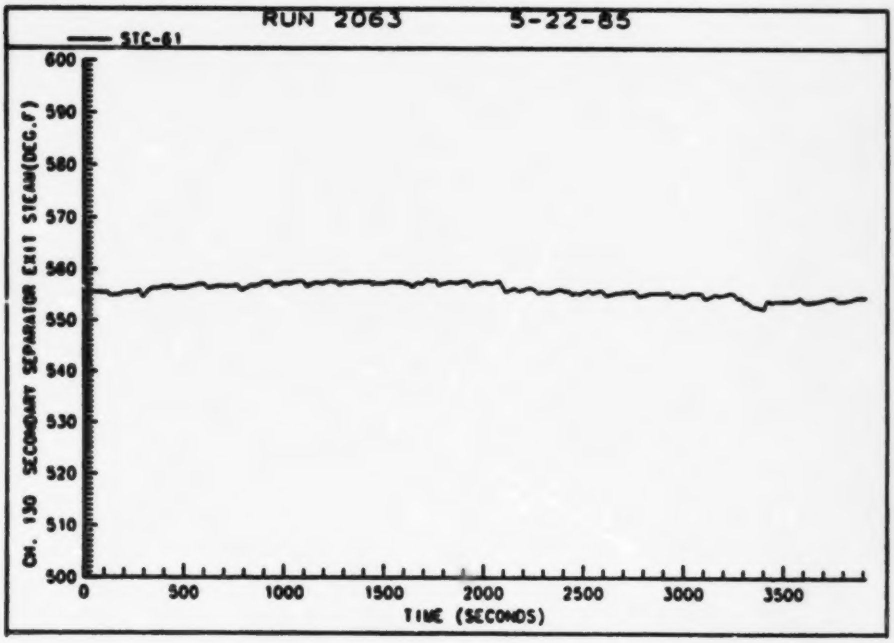

Figure 5-522. Secondary Fluid Temperature (STC-61): Test No. 16 (T-2063)

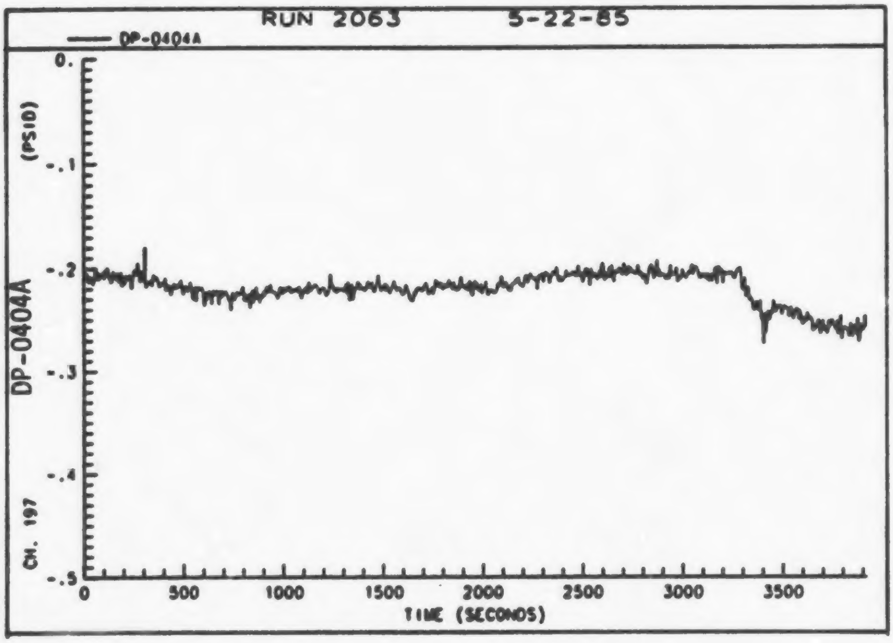

Figure 5-523. Differential Pressure, DP-0404A: Test No. 16 (T-2063)

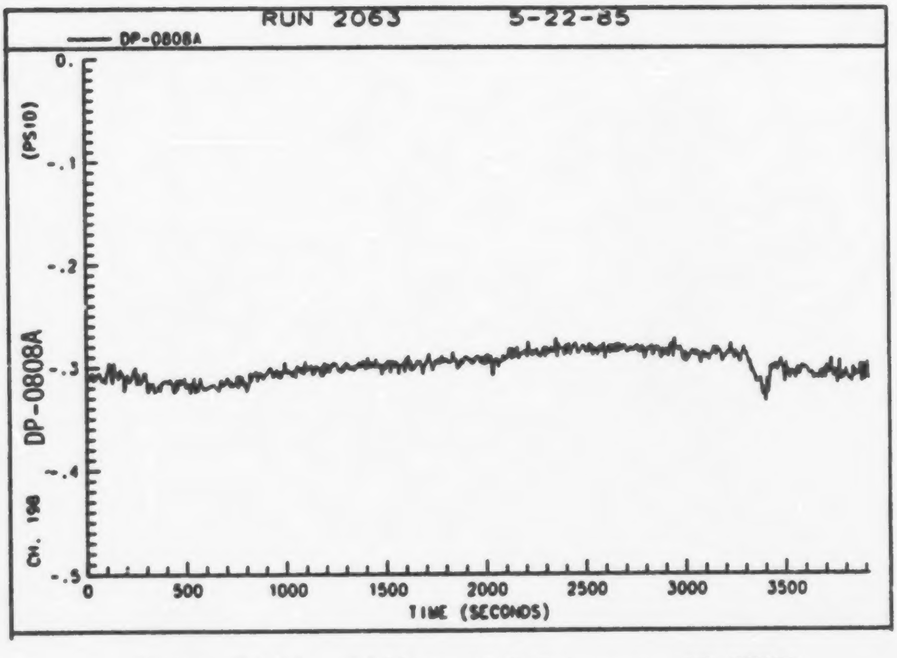

Figure 5-524. Differential Pressure, DP-0808A: Test No. 16 (T-2063)

476

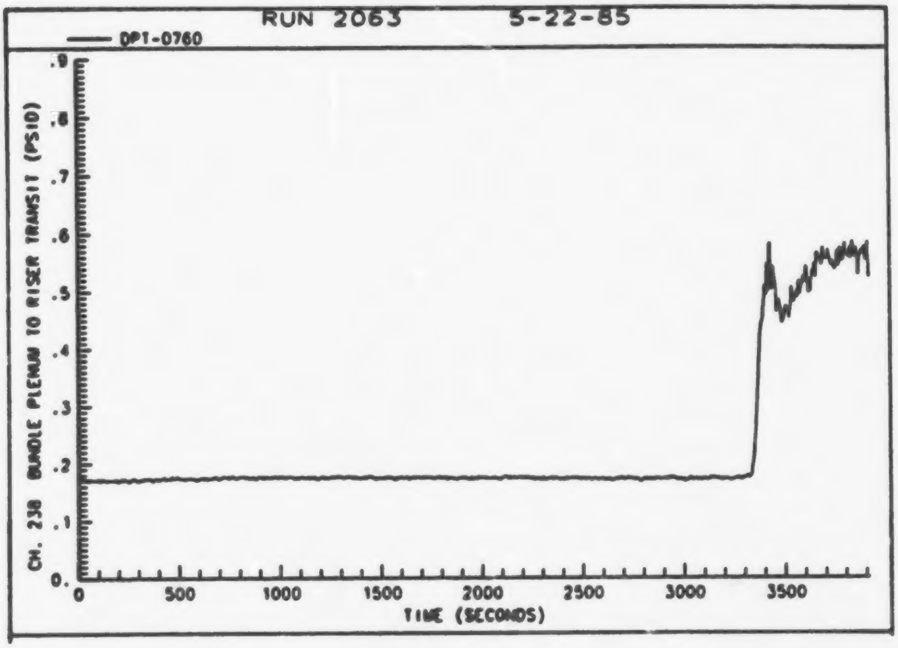

Figure 5-525. Differential Pressure, DP-0760:
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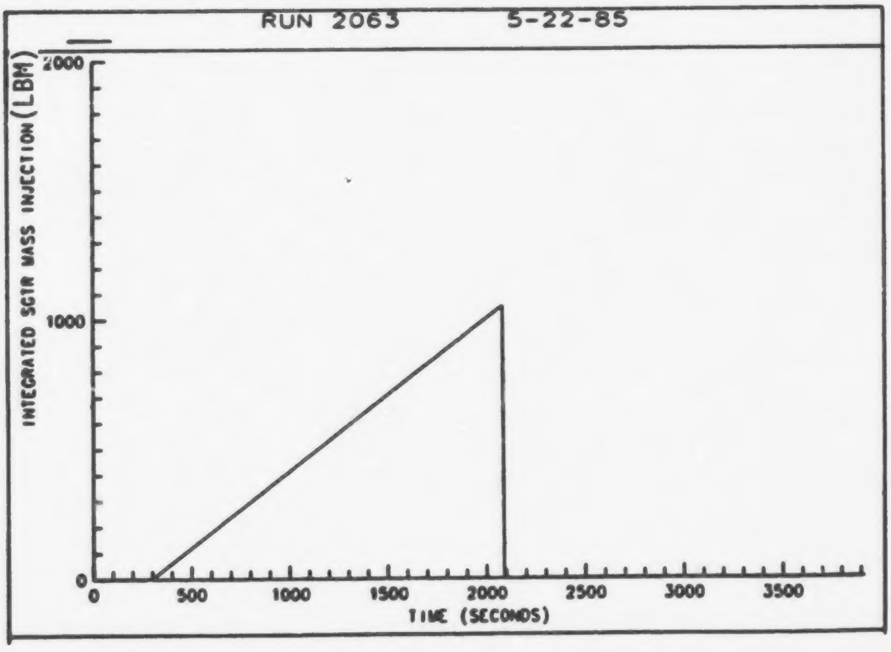

Figure 5-526. Integrated SGTR Flow:
Test No. 16 (T-2063)

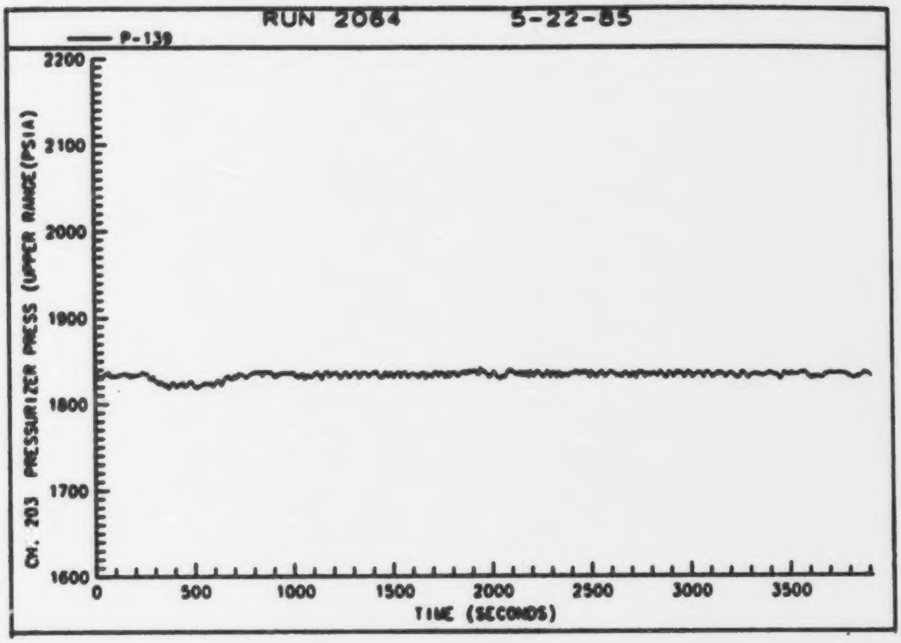

Figure 5-527. Primary System (Pressurizer) Pressure (P-139): Test No. 16 (T-2064)

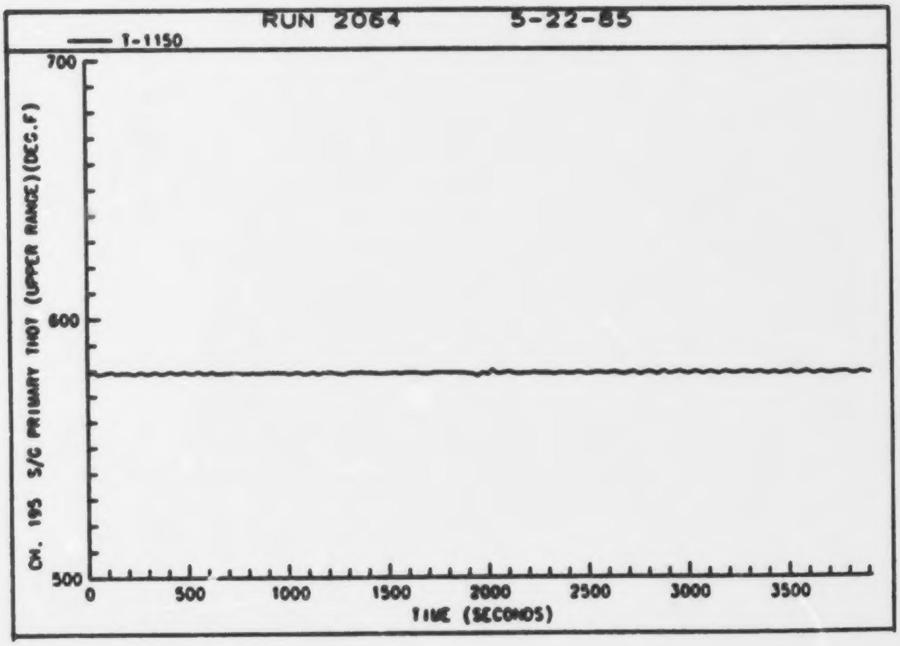

Figure 5-528. Primary Fluid T_{hot} (T-1150): Test No. 16 (T-2064)

478

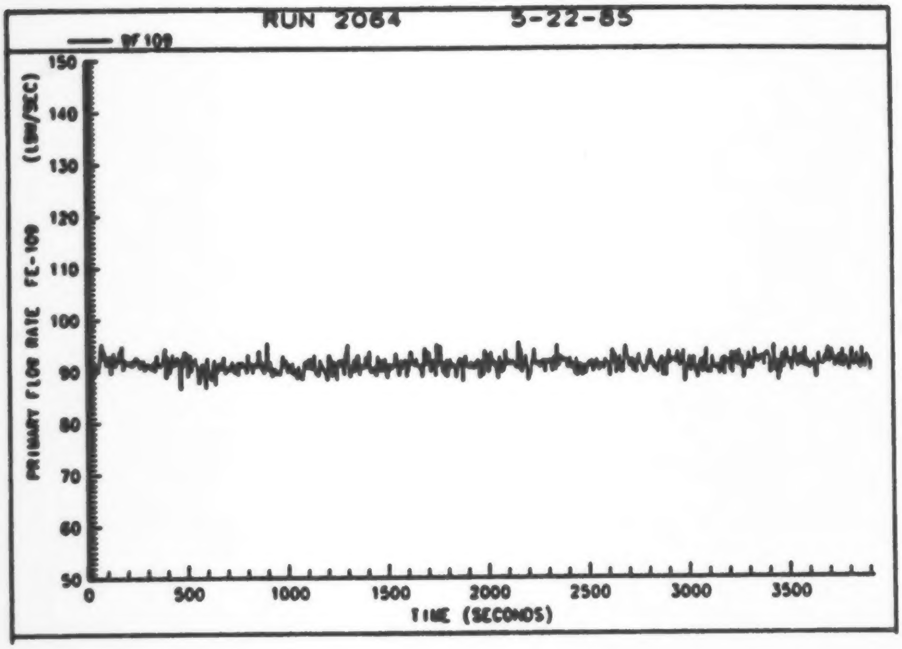

Figure 5-529. Primary Fluid Flow Rate (WF-109): Test No. 16 (T-2064)

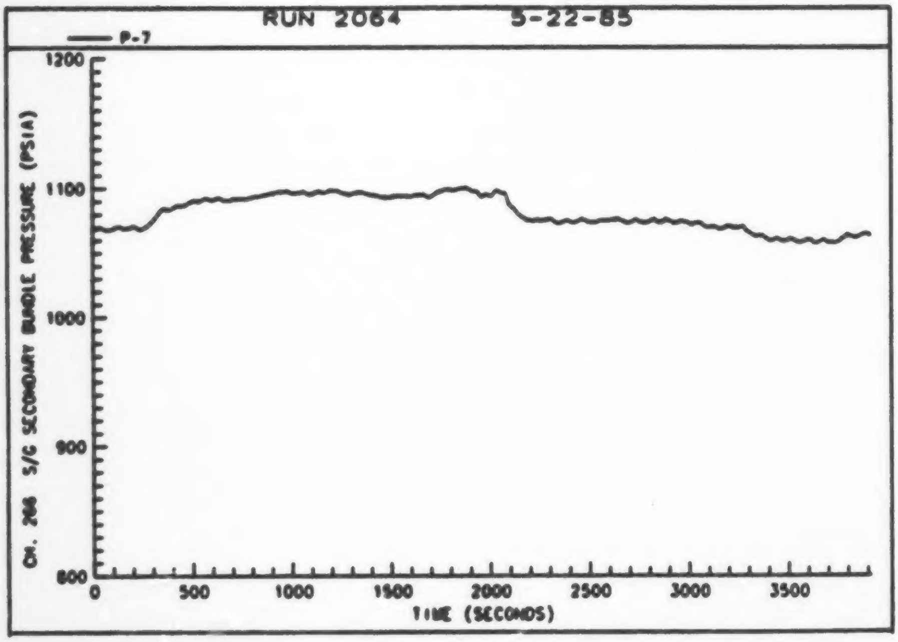

Figure 5-530. Secondary Side Pressure (P-7): Test No. 16 (T-2064)

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479

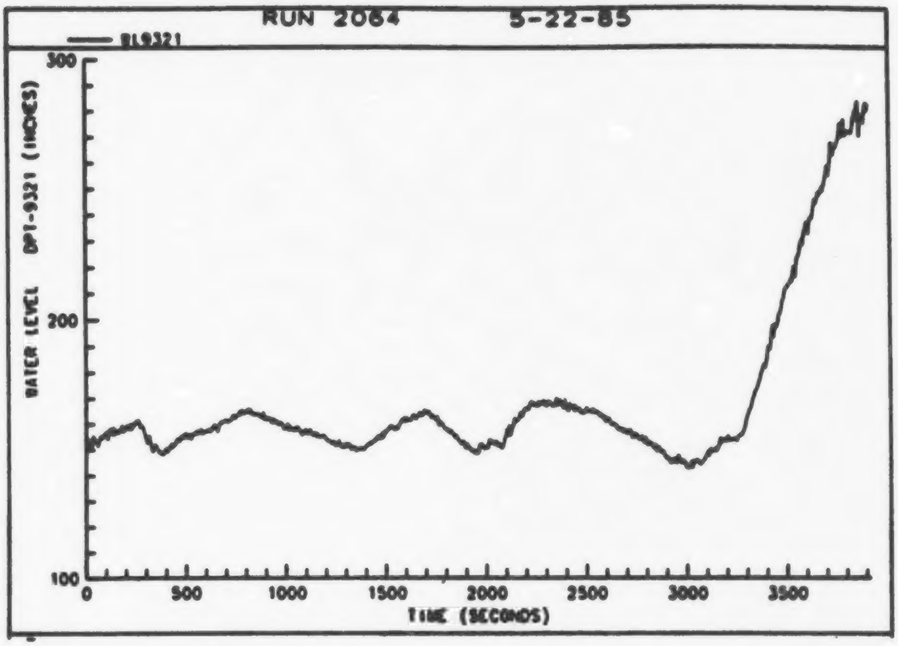

Figure 5-531. Downcomer Water Level - Wide Range (WL-9321)
Test No. 16 (T-2064)

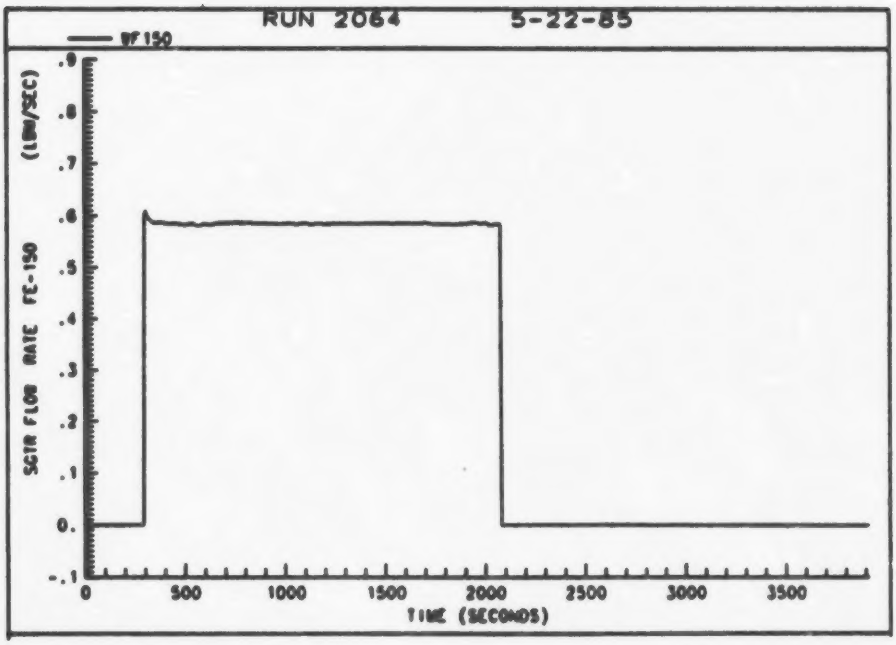

Figure 5-532. SGTR Flow Rate (WF-150): Test No. 16 (T-2064)

480

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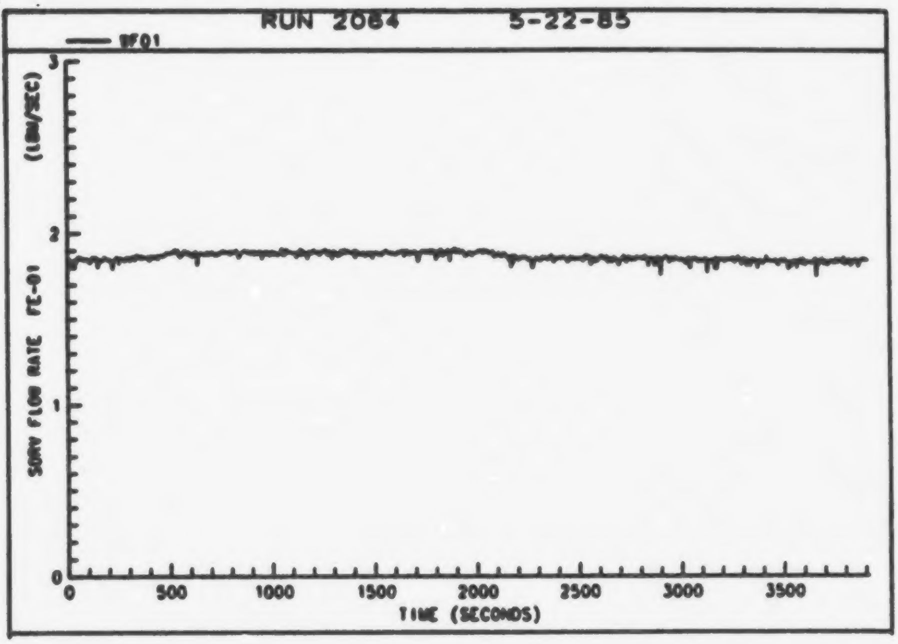

Figure 5-533. SORV Flow Rate (WF-01): Test No. 16 (T-2062)

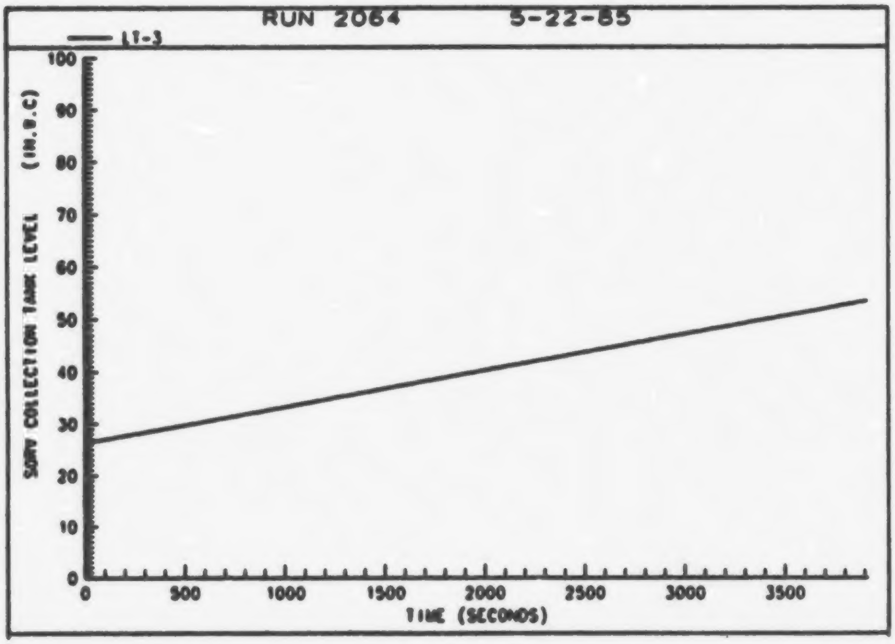

Figure 5-534. SORV Tank Level (LT-3): Test No. 16 (T-2064)

481

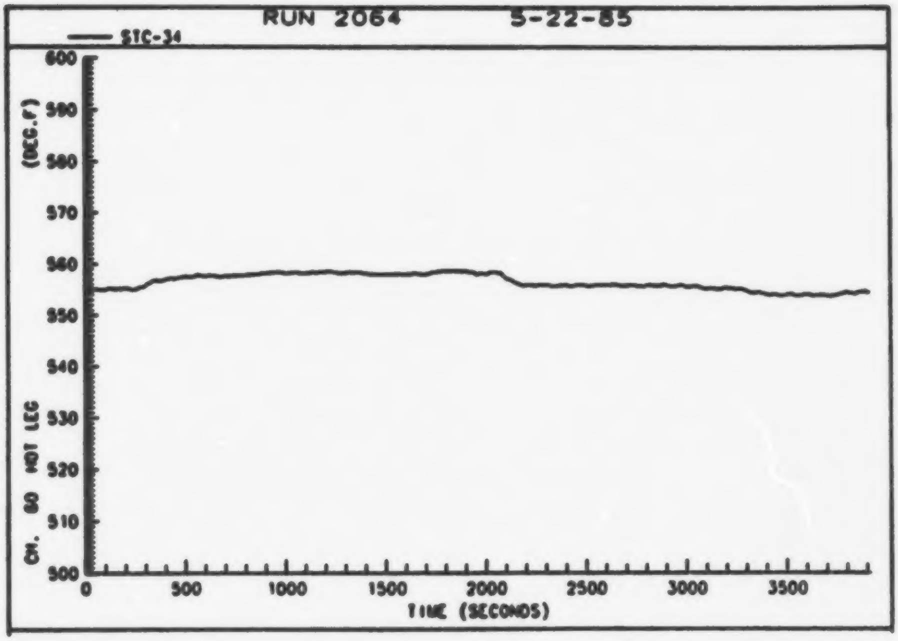

Figure 5-535. Secondary Fluid Temperature (STC-34): Test No. 16 (T-2064)

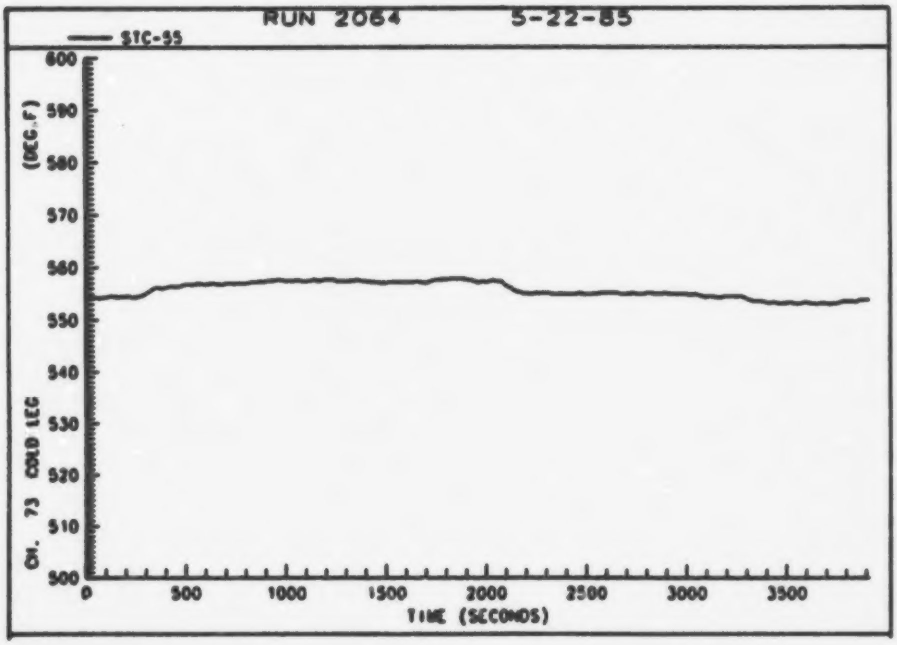

Figure 5-536. Secondary Fluid Temperature (STC-55): Test No. 16 (T-2064)

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482

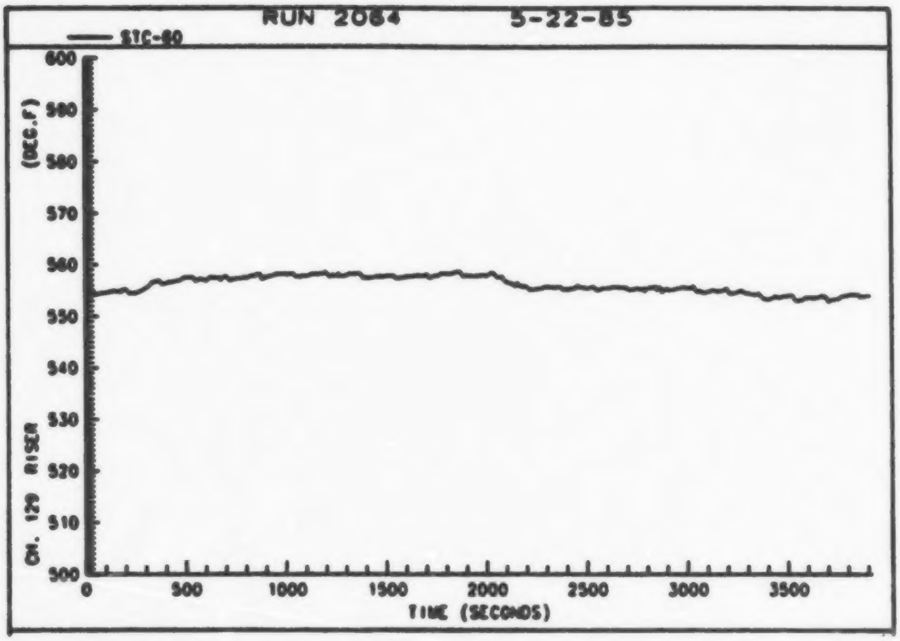

Figure 5-537. Secondary Fluid Temperature (STC-60): Test No. 16 (T-2064)

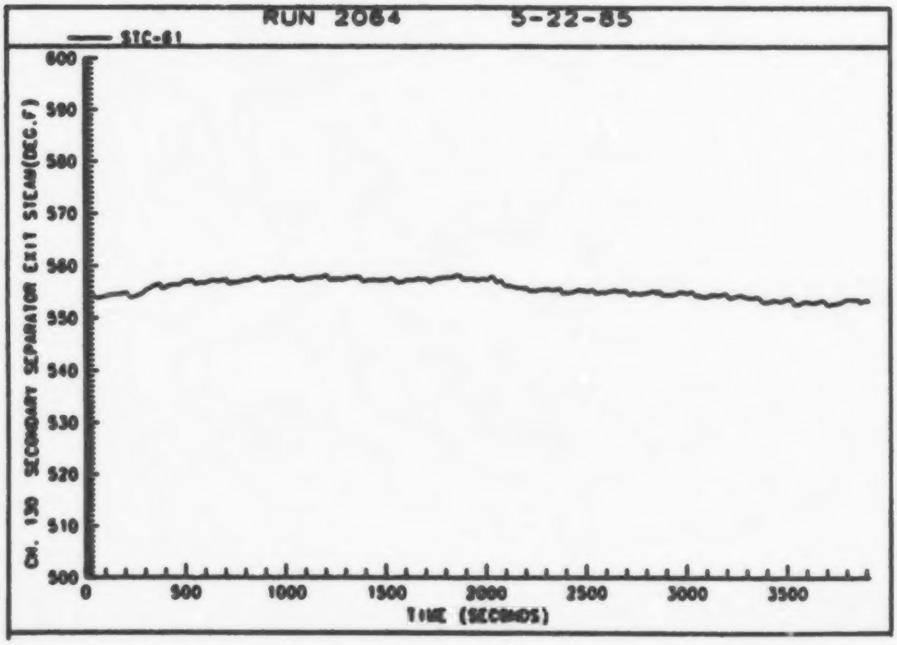

Figure 5-538. Secondary Fluid Temperature (STC-61): Test No. 16 (T-2064)

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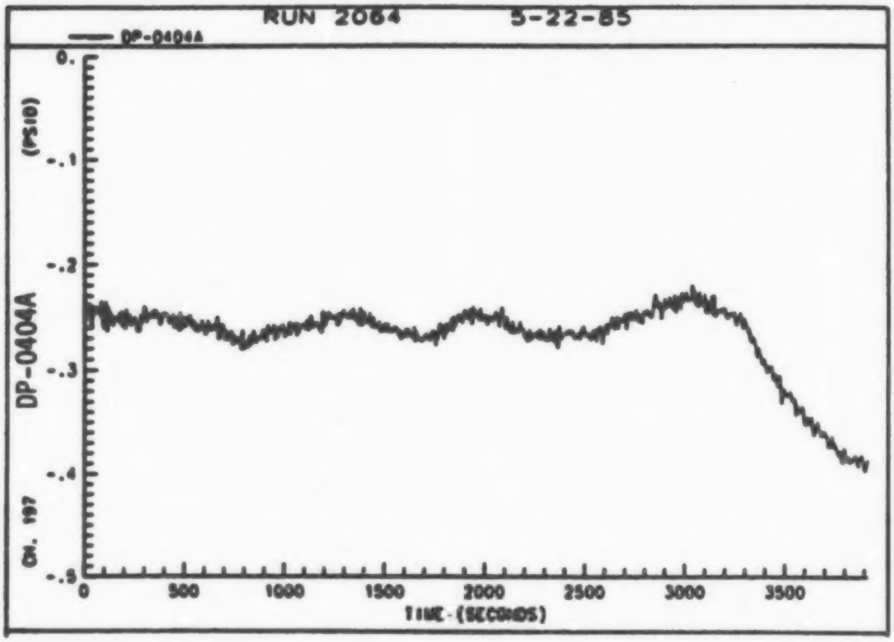

Figure 5-539. Differential Pressure, DP-0404A: Test No. 16 (T-2064)

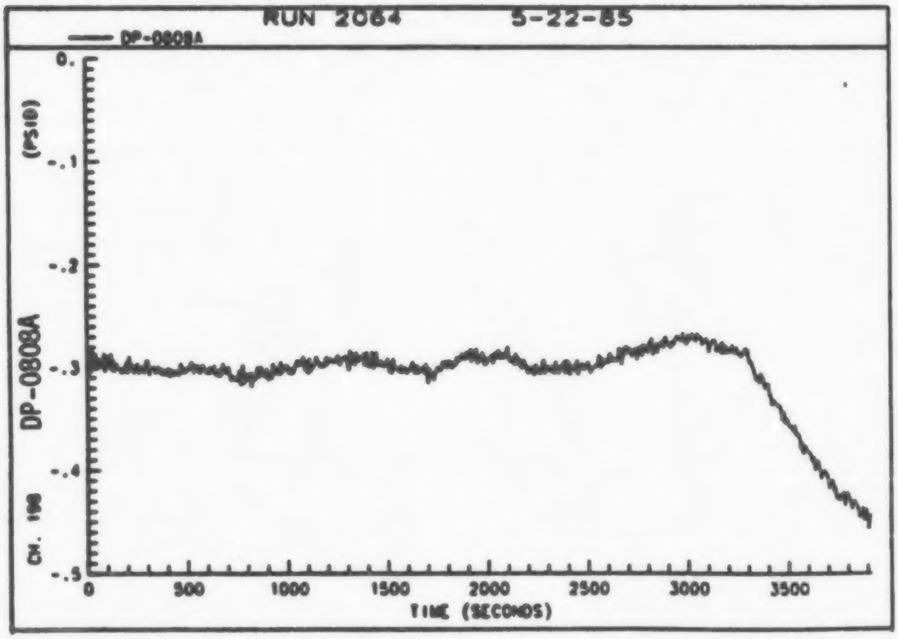

Figure 5-540. Differential Pressure, DP-0808A: Test No. 16 (T-2064)

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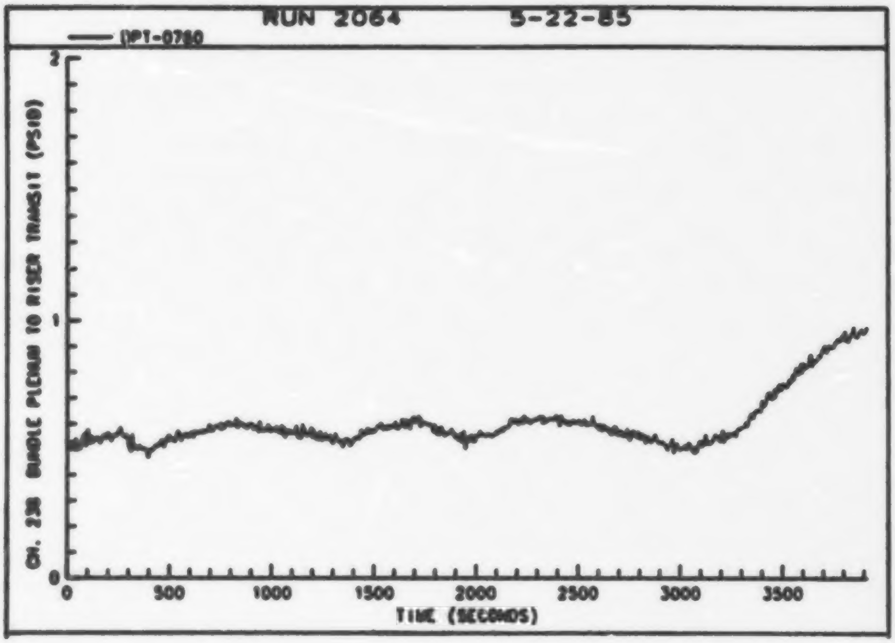

Figure 5-541. Differential Pressure DP-0760: Test No. 16 (T-2064)

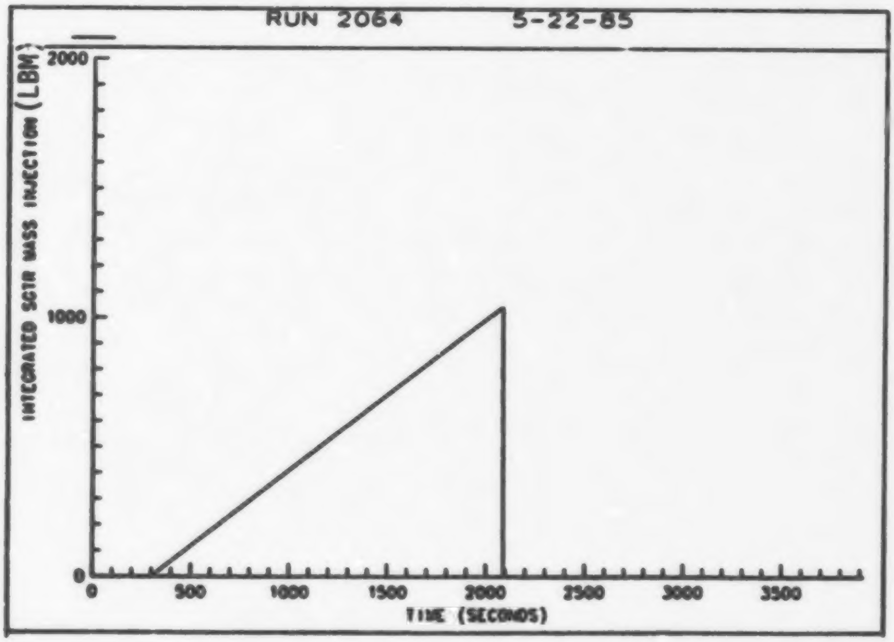

Figure 5-542. Integrated SGTR Flow: Test No. 16 (T-2064)

485

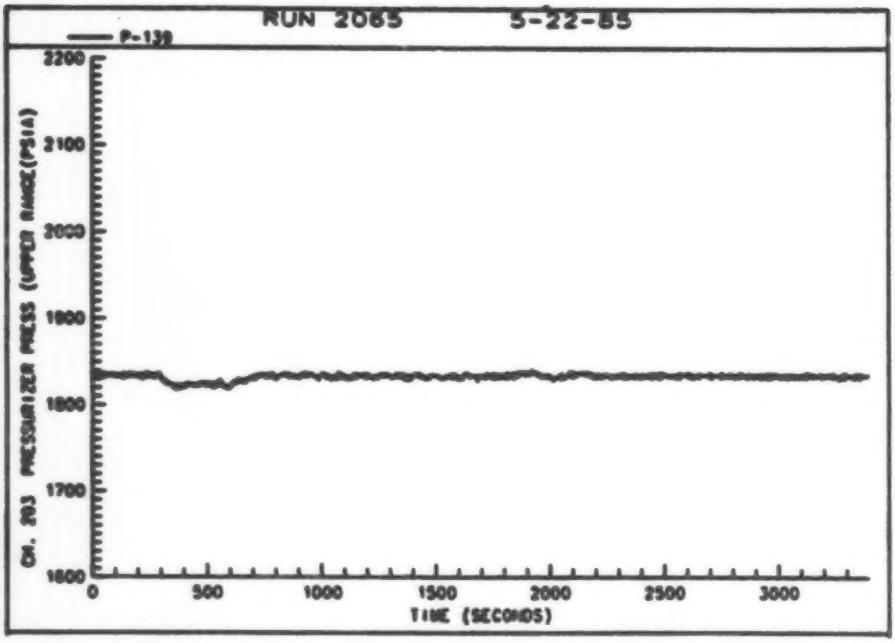

Figure 5-543. Primary System (Pressurizer) Pressure (P-139): Test No. 16 (T-2065)

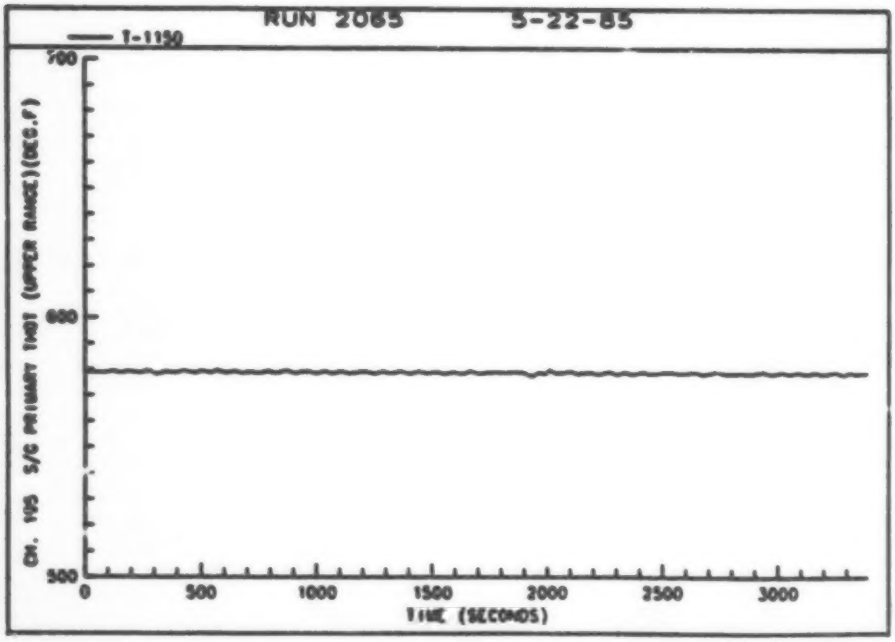

Figure 5-544. Primary Fluid T_{hot} (T-1150): Test No. 16 (T-2065)

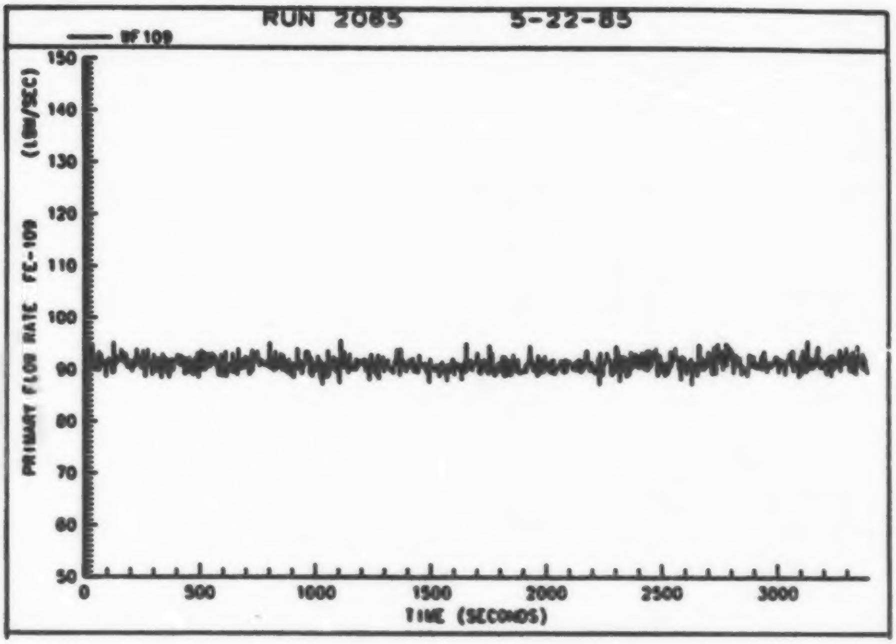

Figure 5-545. Primary Fluid Flow Rate (WF-109): Test No. 16 (T-2065)

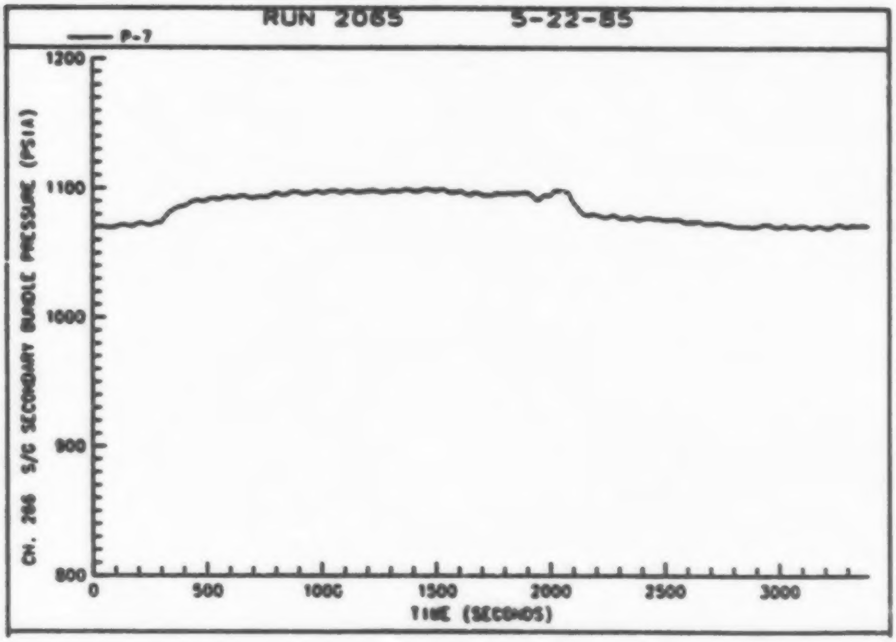

Figure 5-546. Secondary Side Pressure (P-7): Test No. 16 (T-2065)

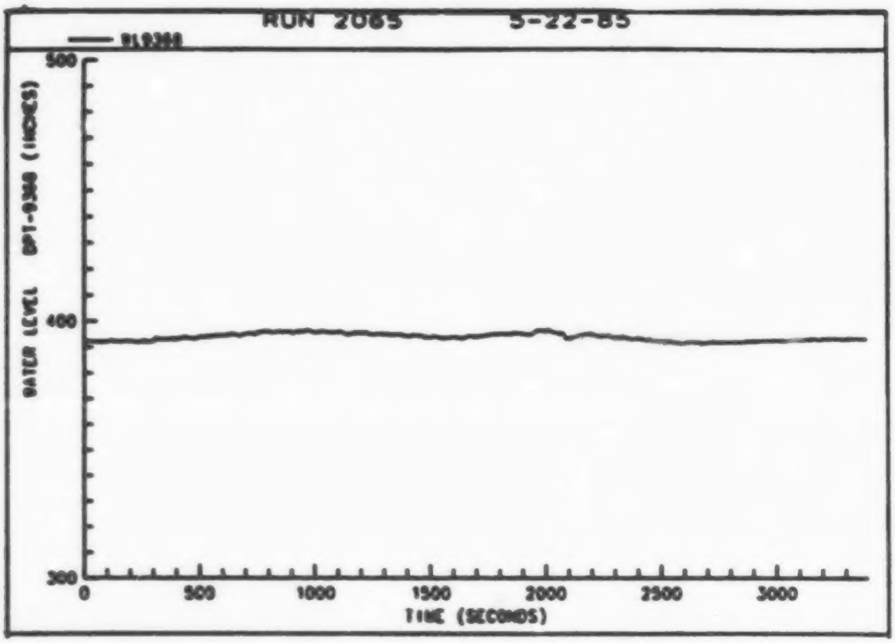

Figure 5-547. Downcomer Water Level - Narrow Range (WL-9360): Test No. 16 (T-2065)

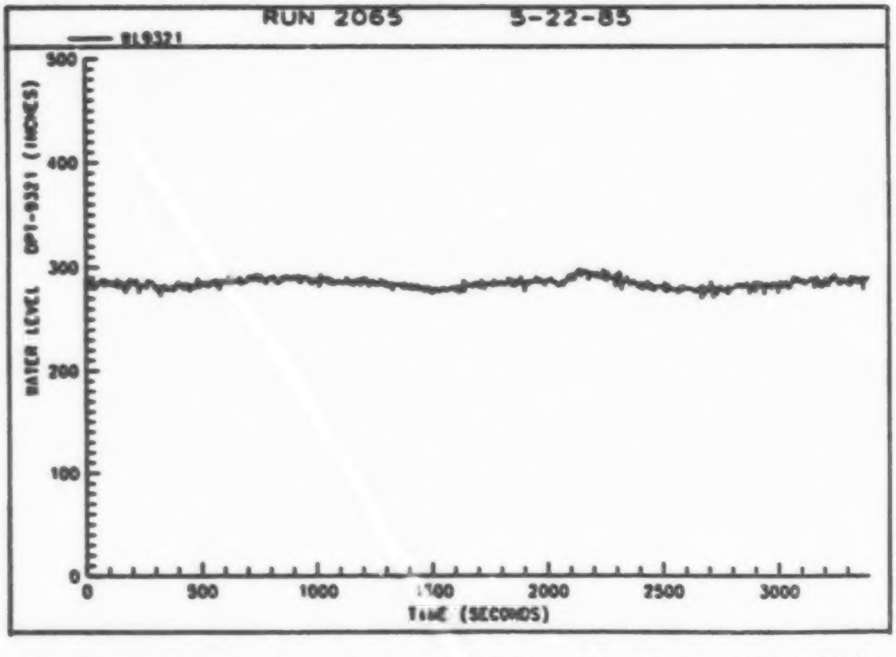

Figure 5-548. Downcomer Water Level - Wide Range (WL-9321): Test No. 16 (T-2065)

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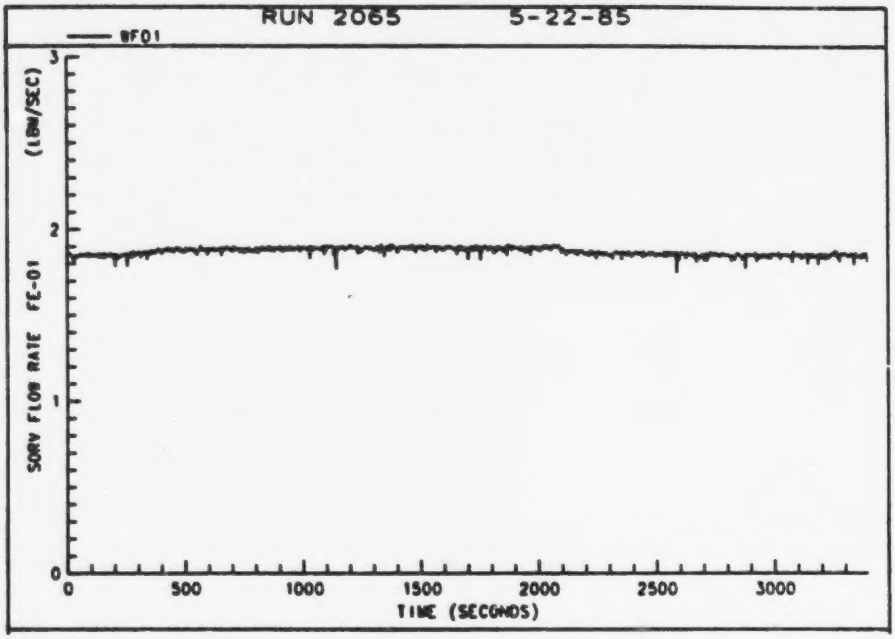

Figure 5-549. SORV Flow Rate (WF-01): Test No. 16 (T-2065)

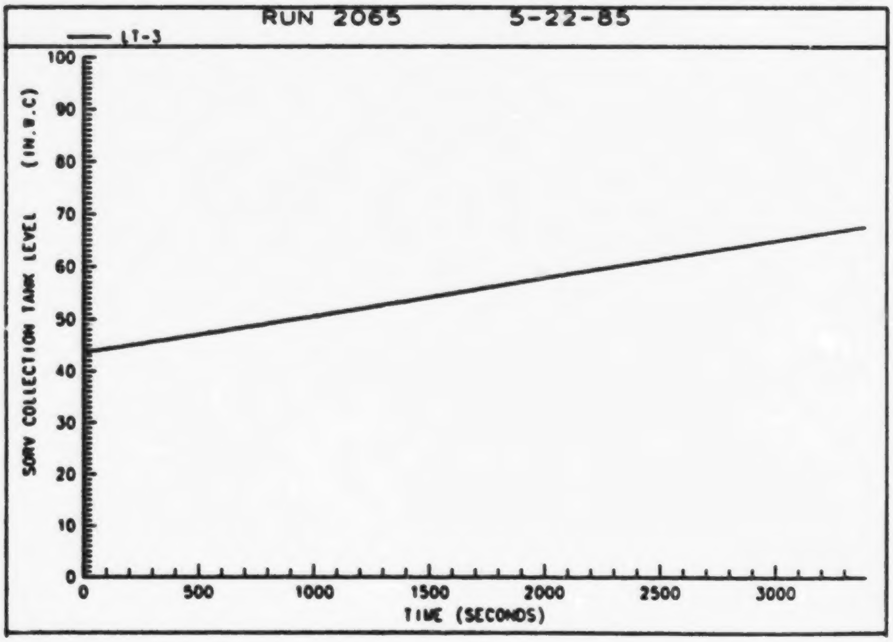

Figure 5-550. SORV Tank Level (LT-3): Test No. 16 (T-2065)

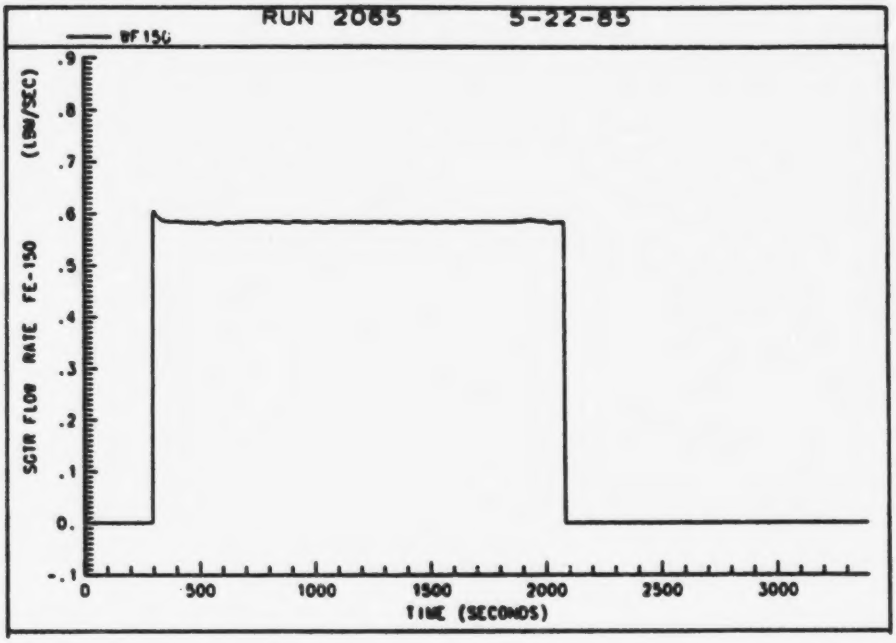

Figure 5-551. SGTR Flow Rate (WF-150): Test No. 16 (T-2065)

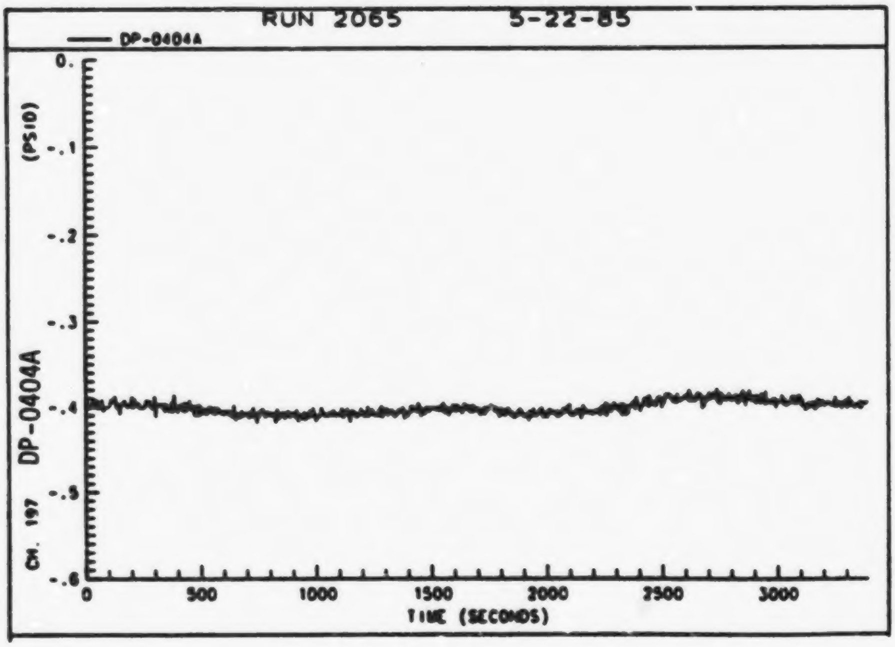

Figure 5-552. Differential Pressure, DP-0404A: Test No. 16 (T-2065)

490

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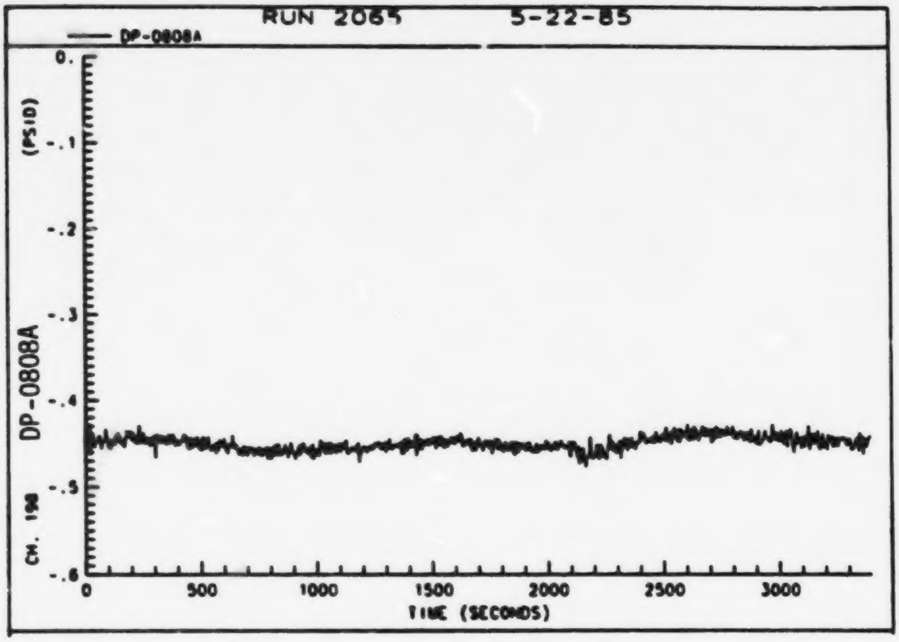

Figure 5-553. Differential Pressure, DP-0808A: Test No. 16 (T-2065)

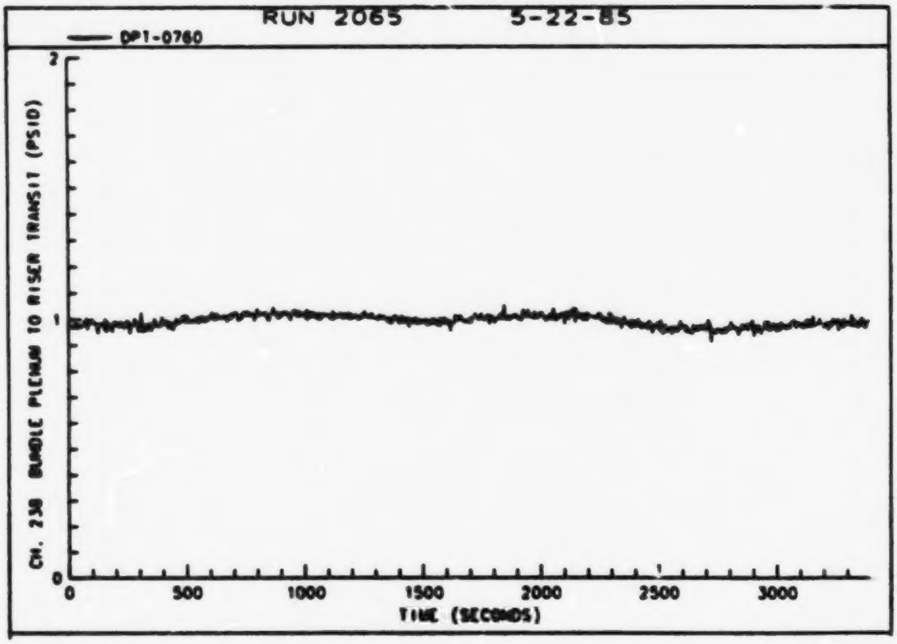

Figure 5-554. Differential Pressure DP-0760: Test No. 16 (T-2065)

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491

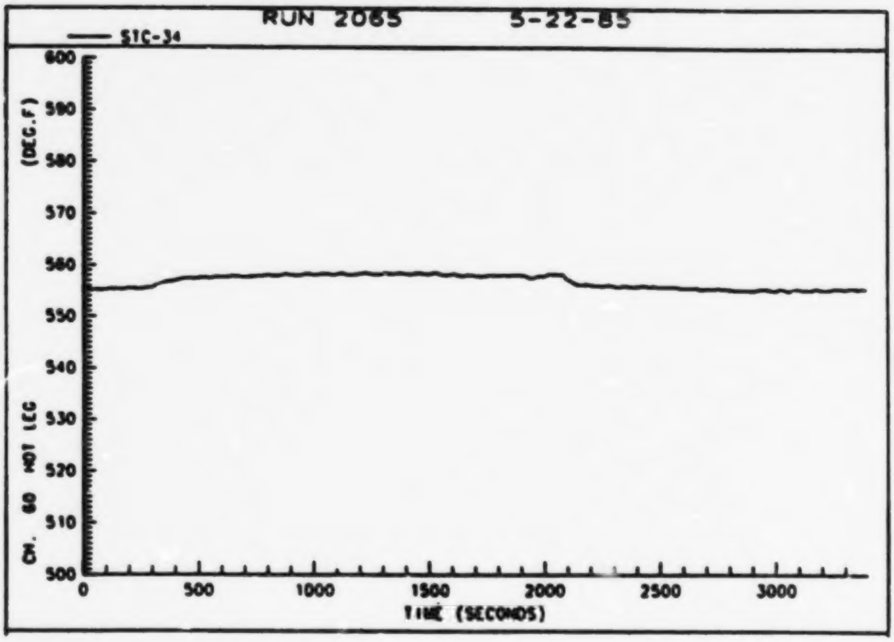

Figure 5-555. Secondary Fluid Temperature (STC-34): Test No. 16 (T-2065)

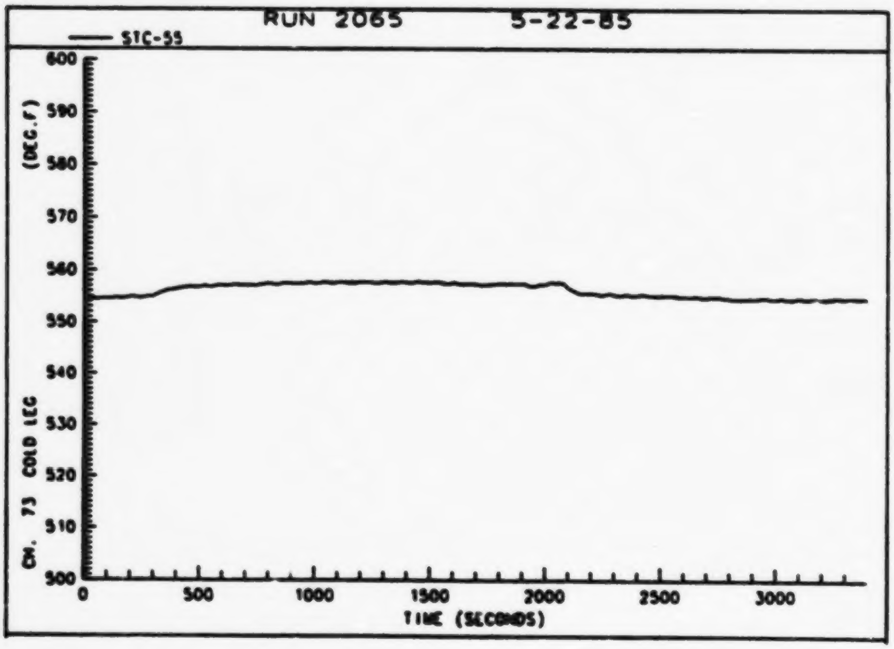

Figure 5-556. Secondary Fluid Temperature (STC-55): Test No. 16 (T-2065)

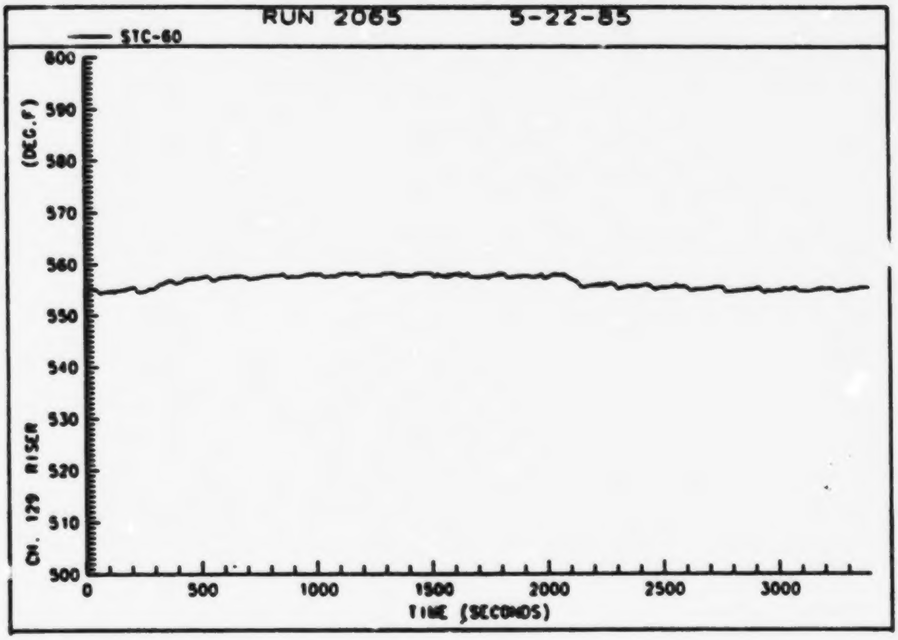

Figure 5-557. Secondary Fluid Temperature (STC-60): Test No. 16 (T-2065)

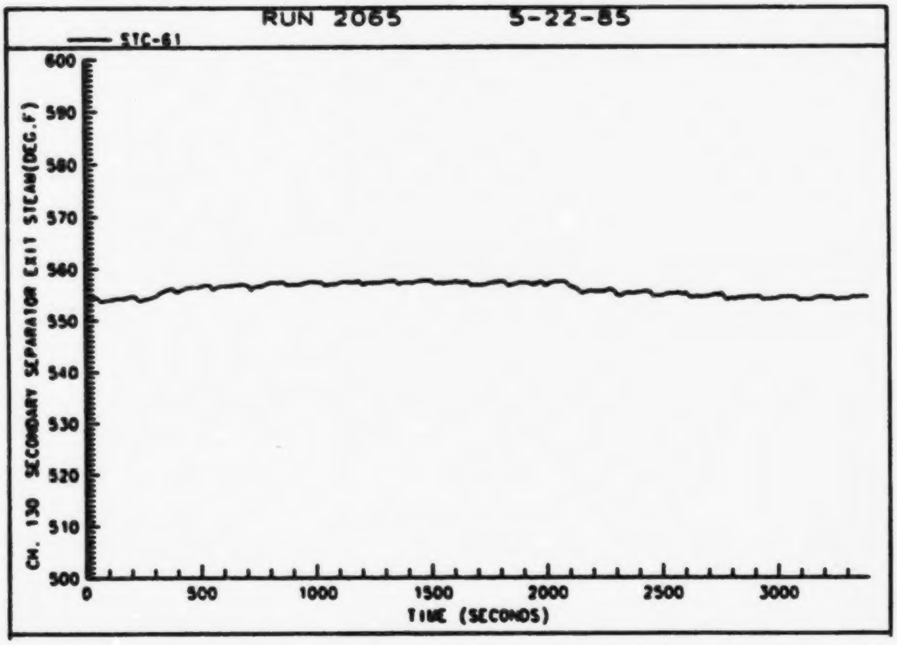

Figure 5-558. Secondary Fluid Temperature (STC-61): Test No. 16 (T-2065)

493

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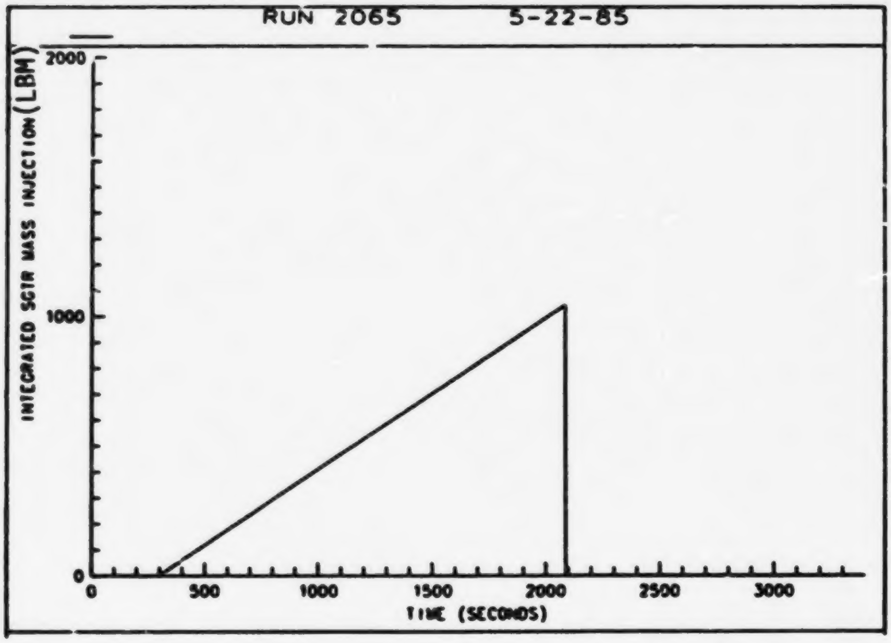

Figure 5-559. Integrated SGTR Flow: Test No. 16 (T-2065)

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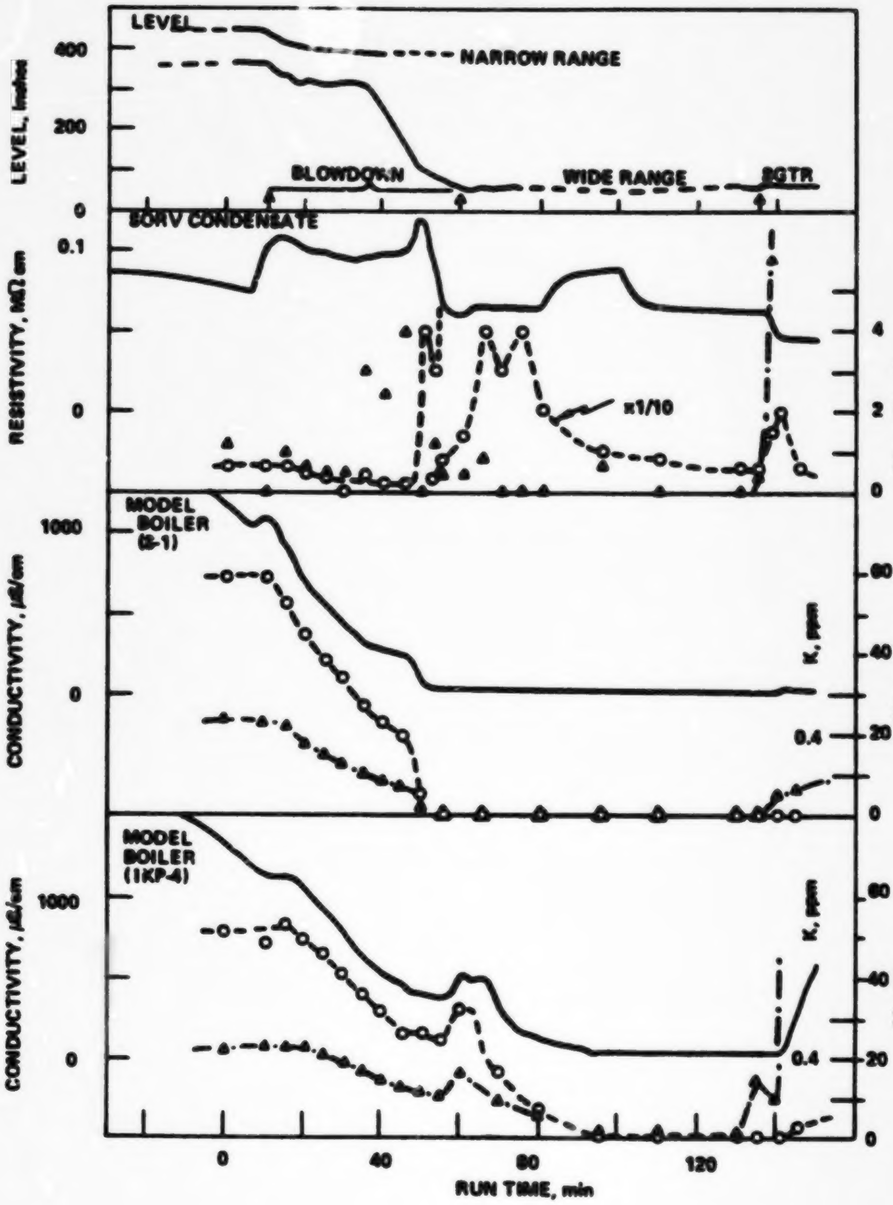

Figure 5-560. Variation in Tracer Concentrations: Blowdown Phase, Test No. 16 (T-2061)

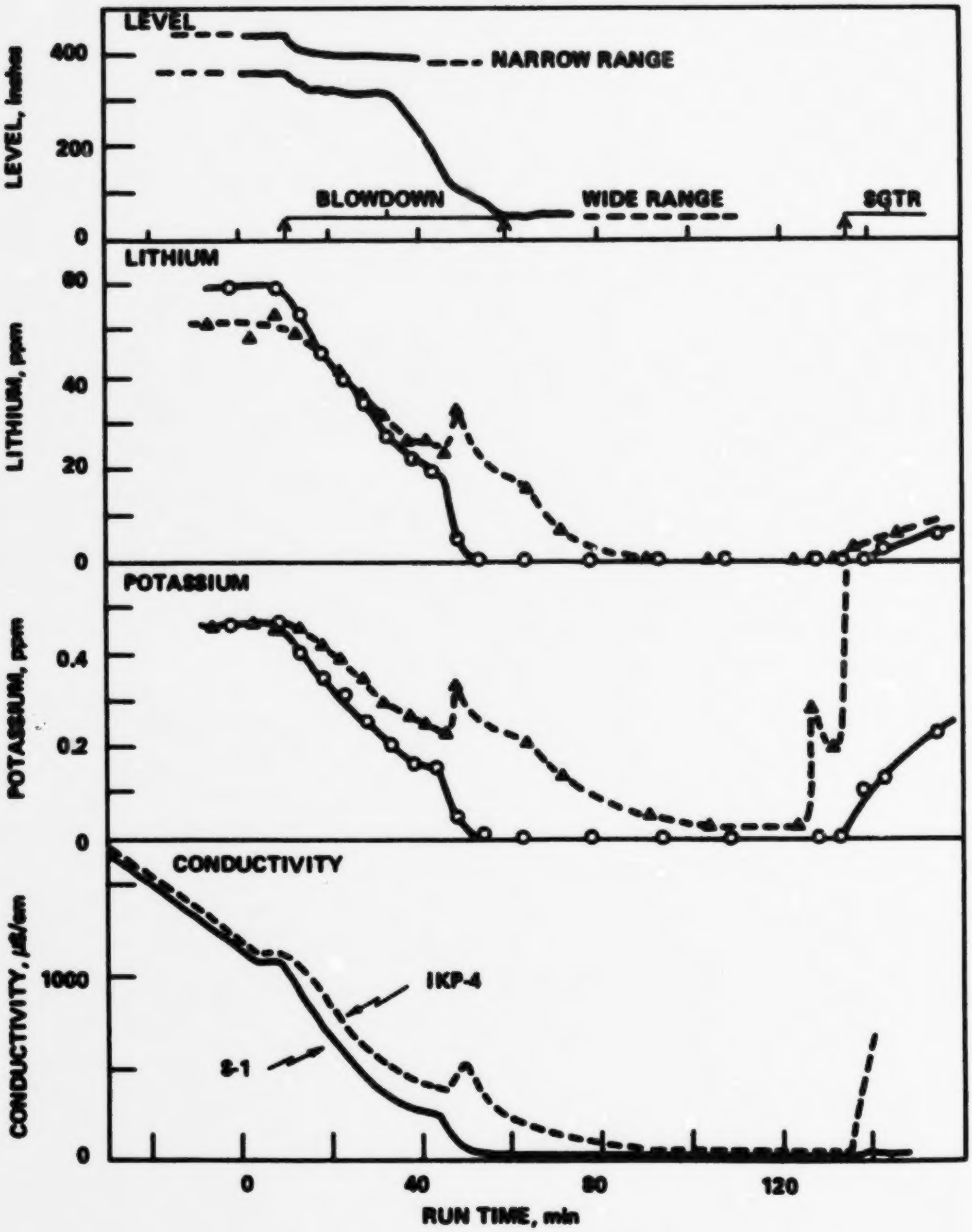

Figure 5-561. Comparison Between S-1 (○) and IKP-4 (▲) Results After Correcting for Sample Line Delays: Blowdown Phase, Test No. 16 (T-2061)

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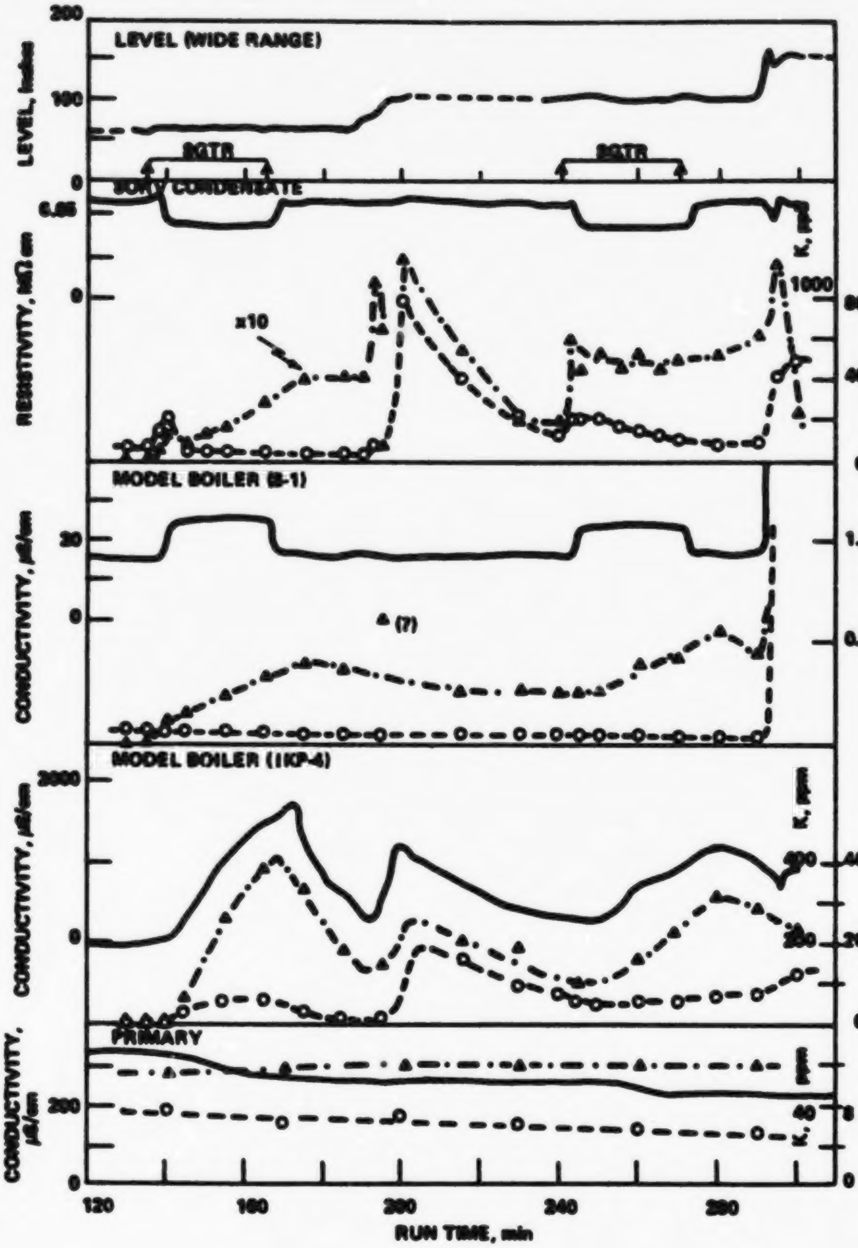

Figure 5-562. Variation in Tracer Concentrations: SGTRs at 60 and 105 in., Test No. 16 (T-2062 and (T-2063)

—·▲—· POTASSIUM CONCENTRATION

—— LEVEL, RESISTIVITY OR CONDUCTIVITY

— o — LITHIUM CONCENTRATION

497

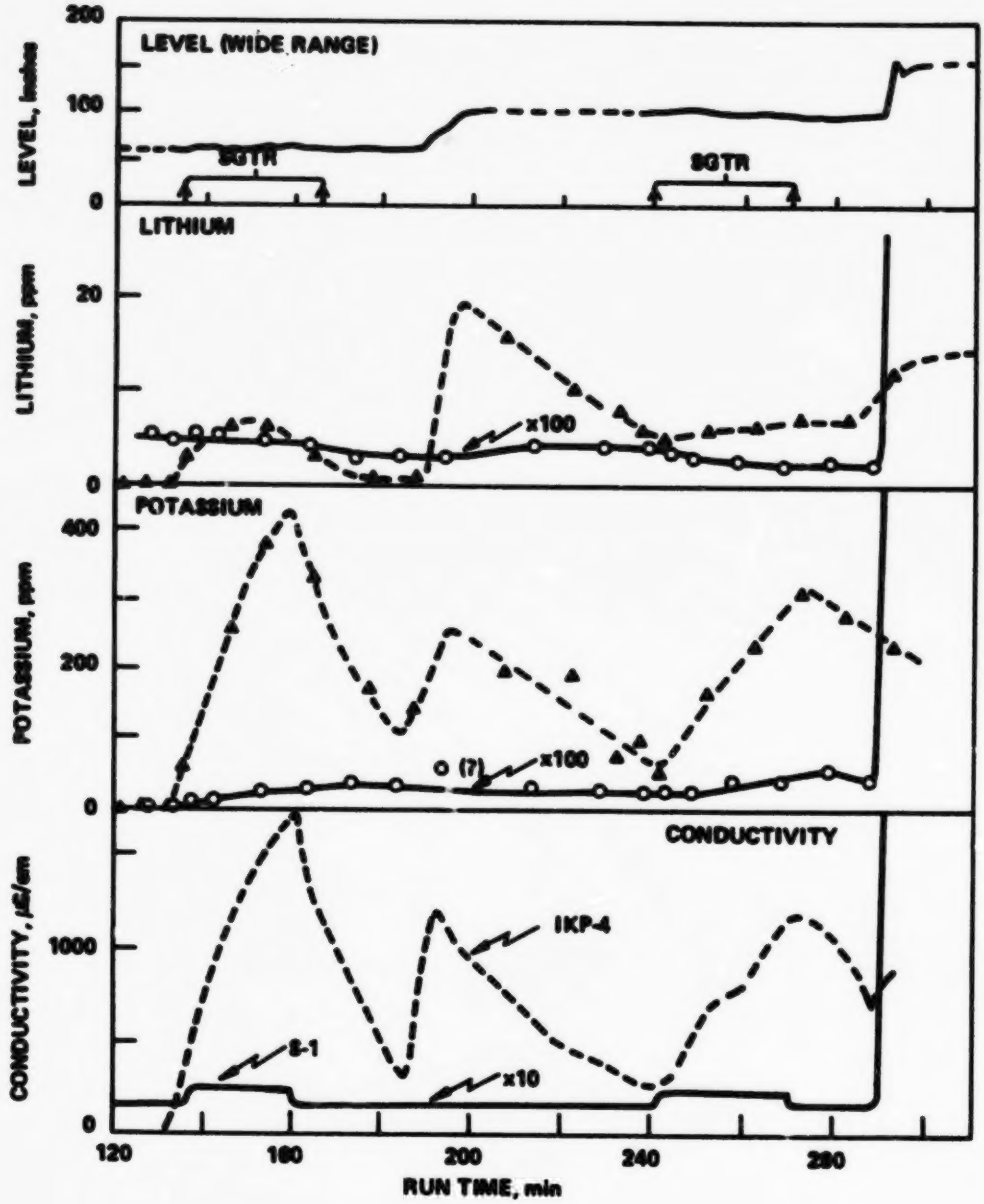

Figure 5-563. Comparison Between S-1 (○) and IKP-4 (▲) Results After Correcting for Sample Line Delays: SGTRs at 60 and 105 in., Test No. 16 (T-2062 and T-2063)

498

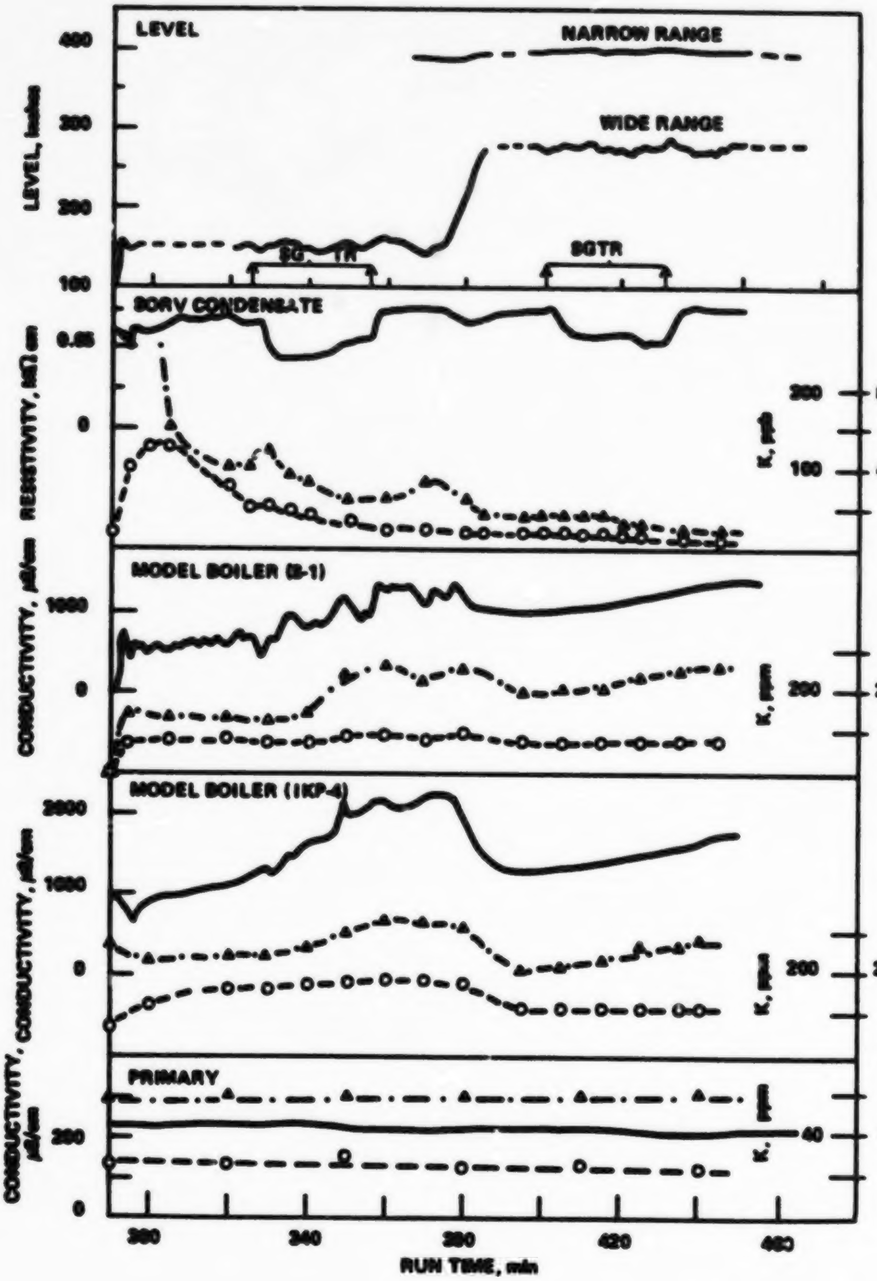

Figure 5-564. Variation in Tracer Concentrations: SGTRs at 155 and 285 in., Test No. 16 (T-2064 and T-2065)

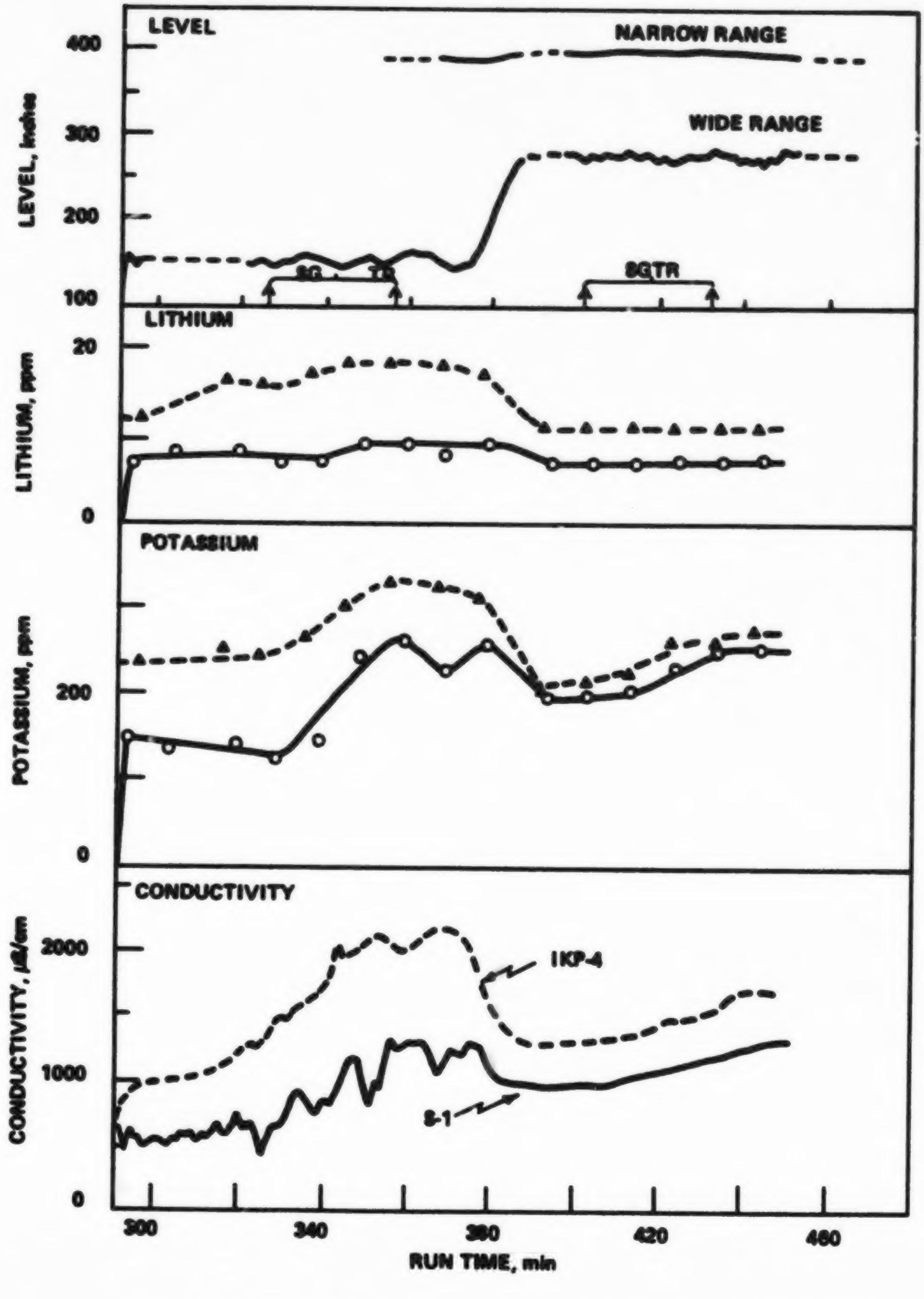

Figure 5-565. Comparison Between S-1 (○) and IKP-4 (▲) Results After Correcting for Sample Line Delays: SGTRs at 155 and 285 in., Test No. 16 (T-2064 and T-2065)

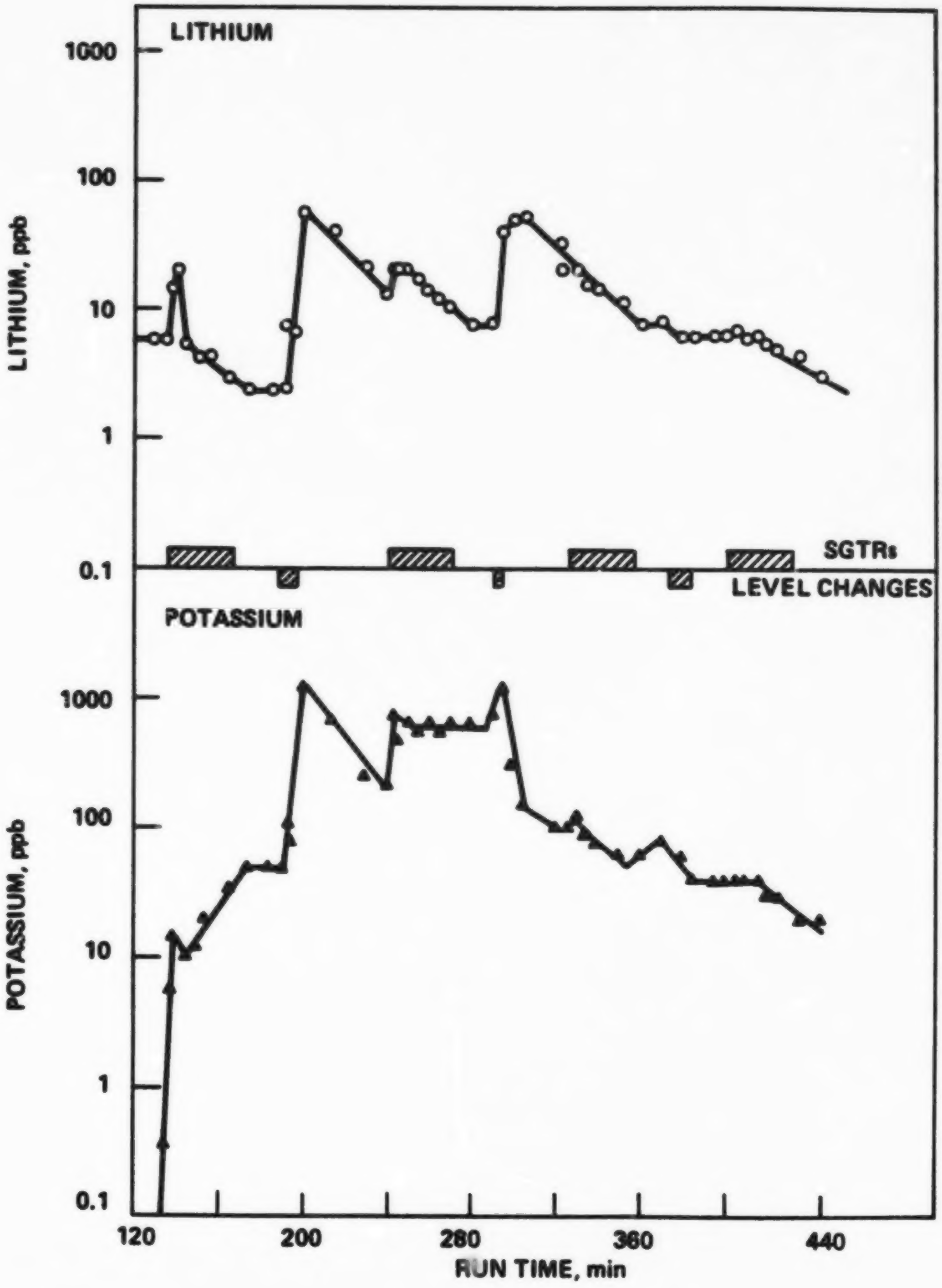

Figure 5-566. Variation in SORV Tracer Concentrations After Correcting for Sample Line Delays: Test No. 16 (T-2061 to T-2065)

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SECTION 6

MASS DISTRIBUTION IN MB-2

To calculate the lithium and potassium concentrations at low water level, when the sample points were operating under two-phase conditions and not taking representative samples, it is necessary to know both the masses of the tracers and the liquid mass in the model boiler at the appropriate downcomer water levels. As the latter could not be measured directly, a series of five tests were performed in which differential pressure measurements were used to calculate the density distribution within the model boiler and, hence, both the liquid and steam masses. These values could then be compared with the total mass in the model boiler, which was measured directly by blowing down through the SORV condenser and weighing the discharge.

The target plant conditions for the steady-state period prior to blowdown were as follows:

Plant Parameter	Desired Value
Primary pressure	1850 psia (127.6 bar)
Primary T_{hot}	580°F (304°C)
Primary flow rate	91 lbm/hr (41.3 kg/s)
Secondary pressure	1080 psia (74.5 bar)
Water level (panel indication)	58, 100, 150, 280, 442 in. (1.5, 2.5, 3.8, 7.1, 11.23 m)
SORV flow	10%

The actual initial plant conditions are shown in Table 6-1 for the five tests. As indicated in this table, the initial conditions were established with "10% SORV flow", i.e., flow through orifices simulating a 2% and an 8% SLB. The test was initiated by tripping shut the main feedwater flow and the 8% SORV flow. At a later time, which varied from test to test, the 8% SORV flow was restarted to allow depressurization via the 10% (2% + 8%) break. The test was terminated when the secondary side had depressurized to near-atmospheric pressure. The mass of the collected discharge is listed in Table 6-2 and is shown plotted in Figure 6-1.

In these tests (as in the other Phase II tests) differential pressure measurements were made across a number of axial increments between the tubesheet and the swirl vane. These data were used herein to obtain a density distribution in the model boiler from which the total mass inventory as well as the mass of the liquid in the boiler were calculated.

In the tube bundle region, differential pressure measurements were made across the flow distribution baffle (DP-0102), across each of the six tube support plates (DP-0203, DP-0308, DP-0809, DP-0904, DP-0405, DP-0506), across the U-bend (DP-0607), and between support plates at two locations (DP-0404A, DP-0808A). Pressure tap installations for the latter two measurements were specifically made to permit the determination of void fractions at these elevations in the bundle region. Differential pressure measurements were also made between the top of the U-bend and a point in the riser (DP-0760), and between two points in the riser (DP-6160). (The locations of the pressure taps are shown in Figures 3-7 and 3-10.)

In calculating the densities for the model boiler, the assumption was made that the frictional, form and accelerational components of the measured pressure differentials were negligible, that is, $DP_{total} \sim \Delta P_{elevational}$. Thus, average densities were calculated from $DP_{Z1-Z2}/\Delta Z$ where DZ = Z2-Z1 = distance between pressure taps. The calculated densities, plotted against average tap elevation, (Z1+Z2)/2, are shown in Figures 6-2 to 6-6 for tests T-2055 - T-2059. From these figures, density values were read off and void fractions (α) calculated for every 20 in. increment between the tubesheet and the point where $\alpha = 1$. The 'collapsed water levels' for each 20 in. increment (20" $(1-\alpha)$) were then summed up to obtain the collapsed water level for the model boiler. The model boiler volume above the 'collapsed water level' and above the downcomer water was assumed to be occupied by saturated steam. In tests T-2055 - T-2058 the thermocouples in the downcomer indicated saturation temperature, so saturated water was assumed in the downcomer. Only in test T-2059 was the water in the downcomer and in part of the bundle region subcooled.

Table 6-2 shows the calculated masses for the tests. The good agreements seen between the calculated total masses and the measured masses gives confidence in the density distributions obtained from the differential pressure data and, hence, the liquid and steam splits derived from the density distributions.

TABLE 6-1

ACTUAL INITIAL CONDITIONS OF MASS BLOWDOWN TESTS(1)

	Test T-2055	Test T-2056	Test T-2057	Test T-2058	Test T-2059
Primary Pressure (psia)	1850	1850	1850	1840	1840
Primary T_{hot} (°F)	594(2)	580	578	578	581
Primary flow rate (lbm/s)	91	91	90	91	91
Secondary pressure (psia)	1060	1085	1090	1070	1070
Water level (in.)	62	104	152.5	285	440
SORV (=SLB break) size	10%	10%	10%	10%	10%

(1) Values read from plots

(2) T_{hot} was raised to increase steam pressure

505

TABLE 6-2

MEASURED AND CALCULATED MASSES IN MB-2

	Test T-2055	Test T-2056	Test T-2057	Test T-2058	Test T-2059
Measured total mass (lbm)	182	303.5	418	640	1026
Calculated total mass (lbm)	205.3	303.4	405	639.3	1207.4
Calculated liquid mass in bundle region (lbm)	71	148.5	236.4	432.6	710.8
Calculated liquid mass in downcomer region (lbm)	32.3	48.6	67.6	119.4	441
Calculated steam mass (lbm)	102	106.3	101	87.3	55.6
Collapsed water level (in.)	41.3	86.3	136.7	249.8	369.9
Discrepancy between calculated and measured total masses (%)	12.8	~ 0	3	-.1	17.7

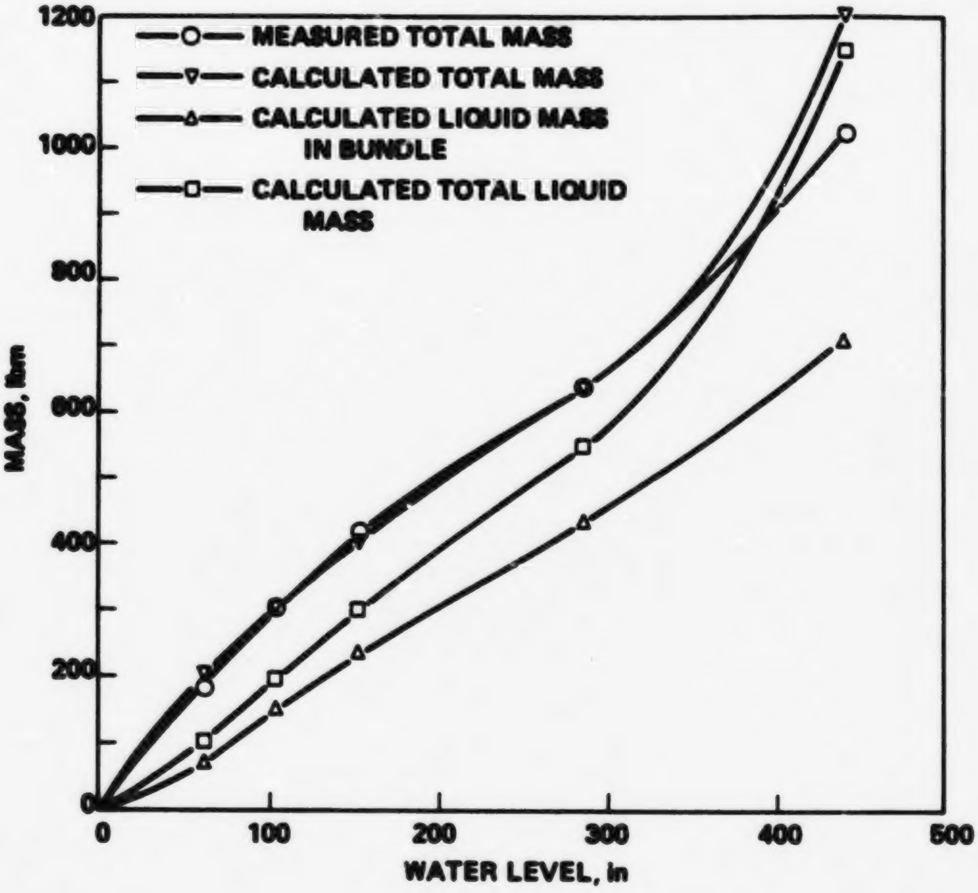

Figure 6-1. Measured and Calculated Masses in MB-2: Tests T-2055 to T-2059

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507

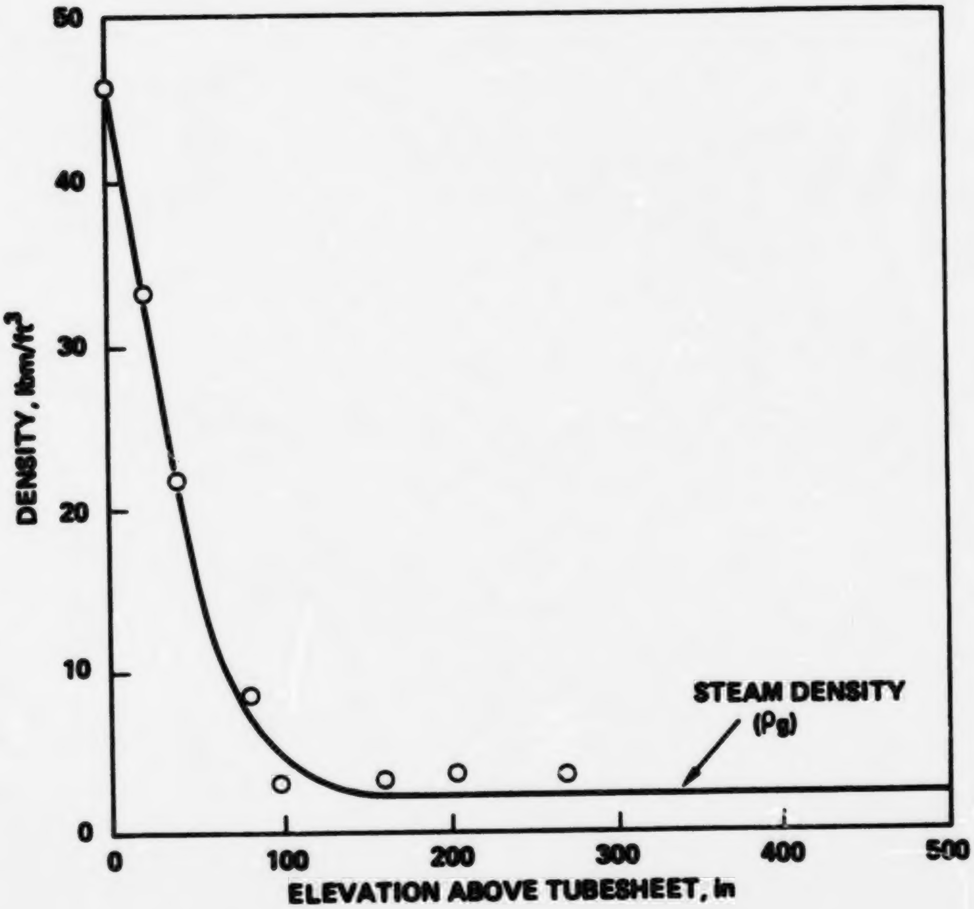

Figure 6-2. Density Distribution in MB-2.Initial Downcomer Level: 62 in. Test T-2055

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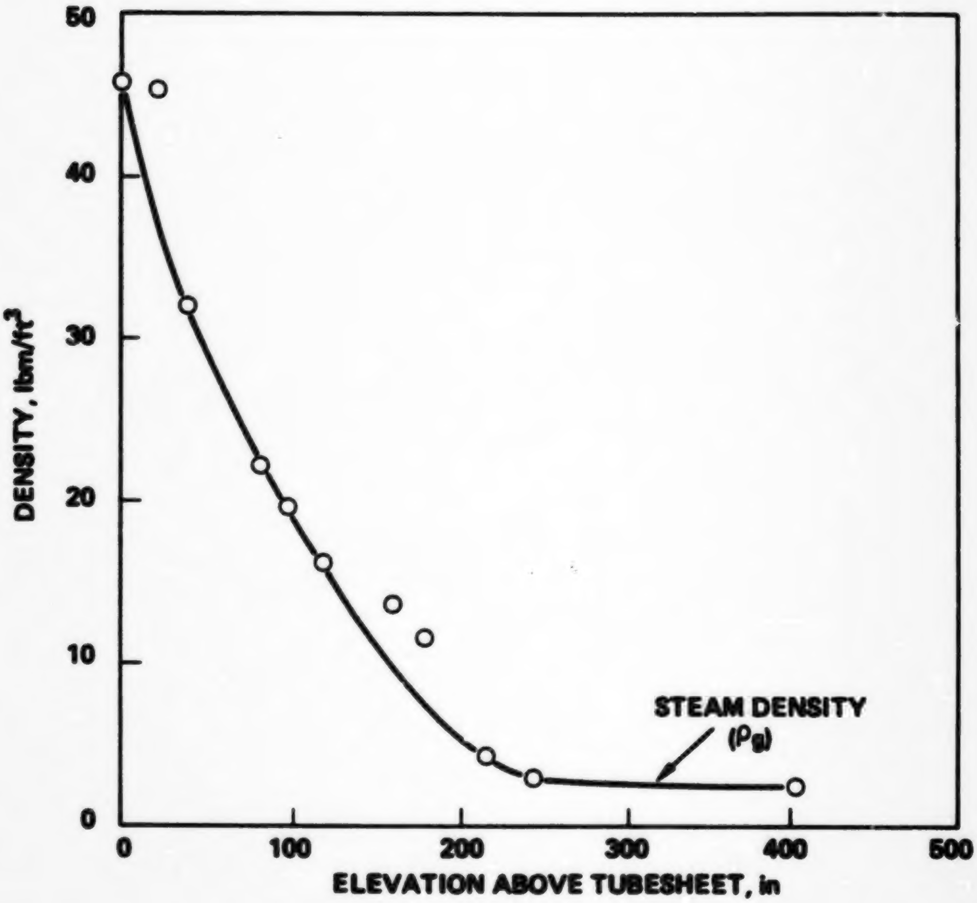

Figure 6-3. Density Distribution in MB-2. Initial Downcomer Level: 104 in. Test T-2056

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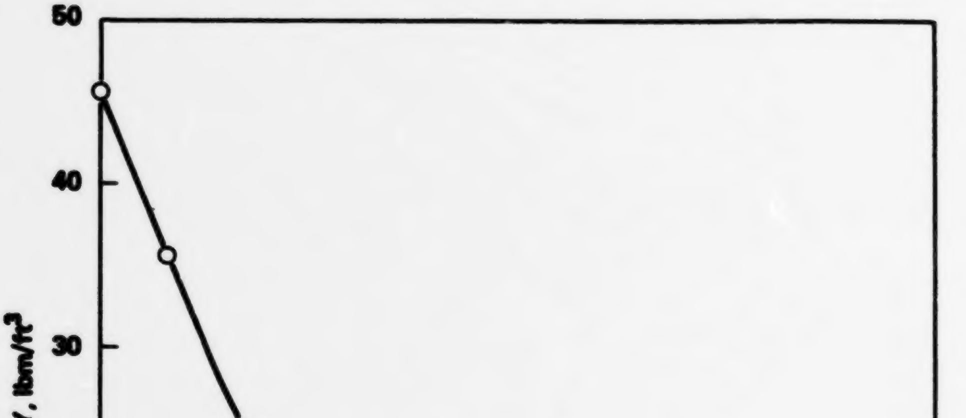

Figure 6-4. Density Distribution in MB-2.Initial Downcomer Level: 152.5 in. Test T-2057

570

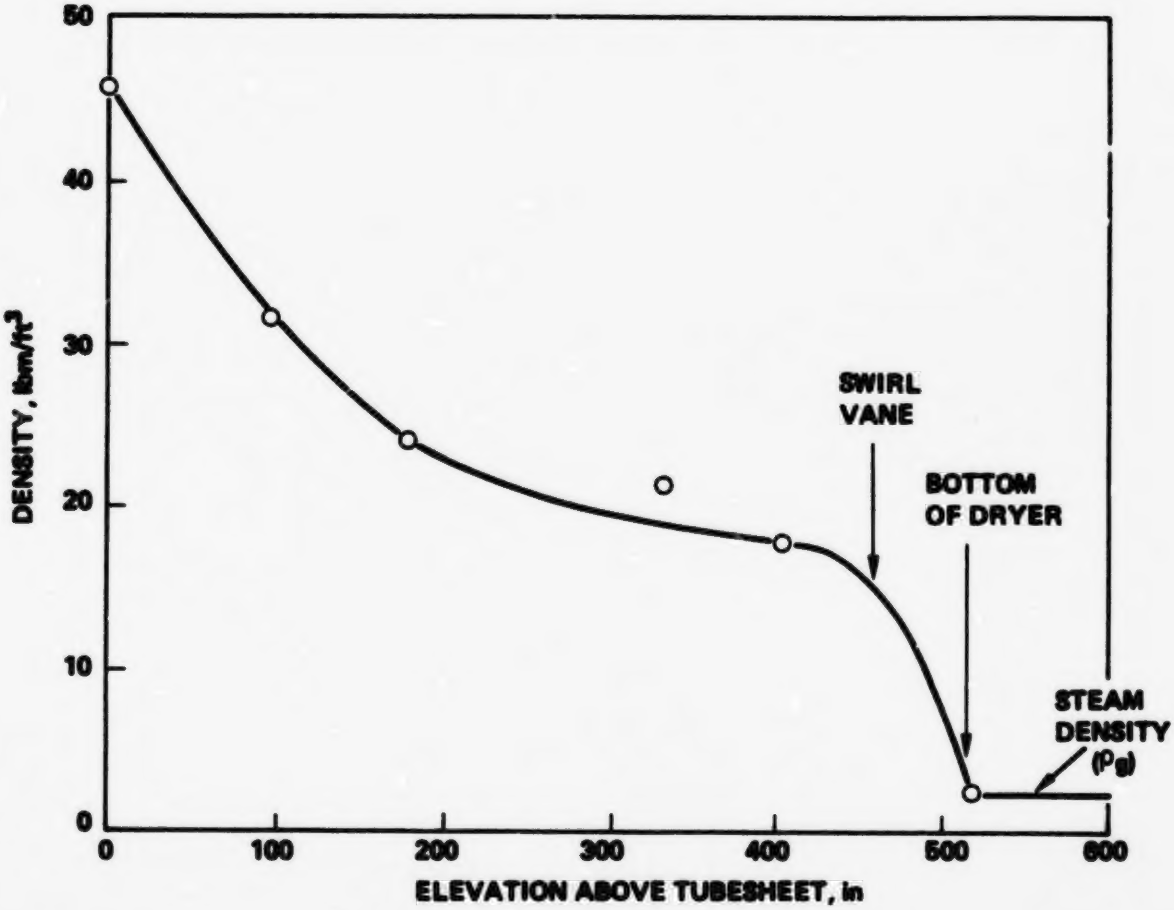

Figure 6-5. Density Distribution in MB-2.Initial Downcomer Level: 285 in. Test T-2058

511

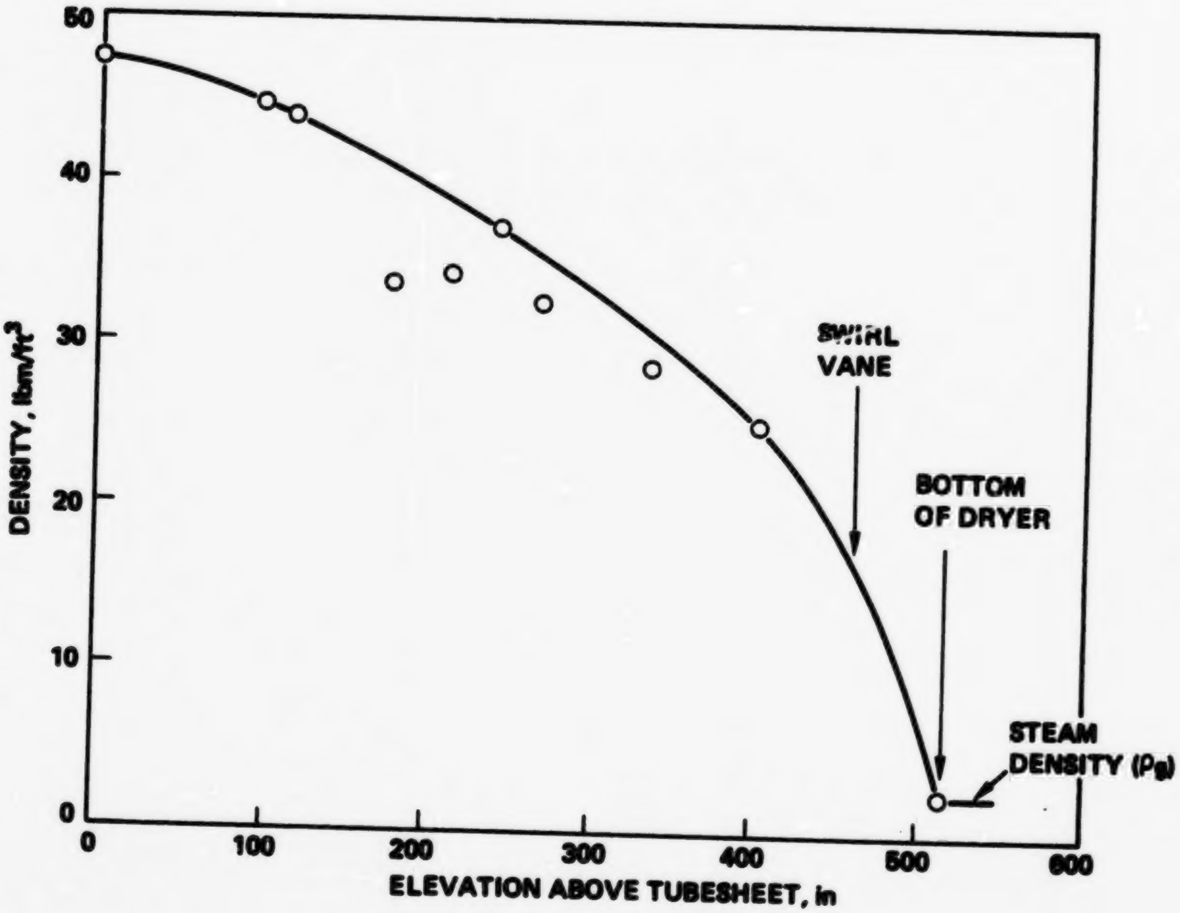

Figure 6-8. Density Distribution in MB-2. Initial Downcomer Level: 440 in. Test 2059

512

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SECTION 7

EVALUATION OF RESULTS

7-1. ANALYTICAL RESULTS

The samples analyzed originated from three different types of water sources, namely condensed SORV steam, single- or two-phase model boiler water and single-phase primary loop water. Due to the differences in origin and in concentration, each type has a different set of analytical requirements and sources of error which need to be considered. These are,

(a) SORV Condensate Samples -

- o The limits of detection and precision of the analytical methods;
- o Interference effects;
- o The risks of sample contamination;
- o The possibility that plateout could occur after sampling;
- o The contribution of steam volatility to the measured carryover.

(b) Model Boiler Water Samples -

- o The consistency of the measured results with those calculated from the mass added to the model boiler;
- o The consistency of the measured concentrations and conductivities;
- o The conditions when the S-1 and IKP-4 sample lines monitor model boiler water alone;

- Under two-phase conditions, what scaling factors need to be applied to convert the results to the true aqueous phase concentrations?

- The consistency of the S-1 and IKP-4 results when good mixing within the model boiler is expected;

- Hideout, either in crevices or on dry surfaces;

- During blowdown, does the model boiler water concentration remain constant as the level is reduced?

(c) Primary Loop Samples -

- The consistency of the measured concentrations and conductivities.

Low Concentration Samples

Throughout the test program most SORV condensate samples were found to contain sub-ppb levels of both lithium and potassium, while slightly higher concentrations were seen in tests at low water level. In the latter tests similar concentrations were also seen on the S-1, IKP-4 and blowdown samples. Generally, at trace levels the principal concerns are how representative are the samples, the limits of detection, precisions and interference effects of the analytical methods and, finally, the risks of contamination and/or plateout during sampling and analysis. With the exception of representative sampling in the case of the SORV condensate samples, these reservations apply to the analyses carried out here. For the SORV condensate samples representative sampling was assured by the total condensation of the SORV steam flow, but with these samples there are additional concerns because of the possibility that the results could be biased high by the volatility of the tracer chemicals or by the slow release of the tracers from contaminated surfaces in the steam spaces of the model boiler.

Of these factors the most important are those associated with the analytical methods. In the present tests the performance of the analytical methods was assessed from a statistical analysis of the calibration data produced during each individual test. These results, see Table 4-1, show that the limit of detection was 0.2 to 0.3 ppb lithium or potassium and the precision 0.1 to 0.2 ppb. Inspection of the data shows that carryover generally exceeded these limits of detection only at low water levels, during the 100% power moisture carryover tests or when these were transient releases. At other times carryover was either comparable with the limit of detection or it was not detectable. For the latter cases the limits of detection have been used to define upper limits for both carryover and bypassing. Even though the limit of detection was 0.2 to 0.3 ppb, a number of the tests (e.g., Test 14) gave no detectable carryover except during the SGTR injection, when carryover increased to values at or just above the detection limit. From the consistency of the results, these are considered to be real effects.

Little evidence for interference effects were seen, nor were any expected from the other constituents present in the samples. However, in Test 5 the presence of high concentrations of hydrazine did cause interference when an attempt was made to analyze potassium at low levels on undiluted S-1 and IKP-4 samples. This was due to a molecular band spectrum centered on the lithium emission line, which caused a small increase in emission at the potassium emission wavelength. The effect disappeared on dilution and did not affect the reported results.

Contamination of the SORV condensate samples was possible, either by cross-contamination from the adjacent sample lines or from the atmosphere. From the start of the program steps were taken to minimize cross-contamination and even though the sample streams often differed in concentration by factors of the order of 1×10^6, only one or two samples were affected. For potassium, contamination from the atmosphere was more difficult to eliminate, due to the location of the test facility on the shore of Tampa Bay. As a result, any airborne particles contained potassium which could either contaminate the samples or affect the analytical method. In practice, contamination of the SORV condensate samples occurred on a number of occasions, but not with a

515

frequency that affected the overall results. However, in two tests, Tests 1 and 16, an increase in the general level of particulates is thought to be responsible for the increased levels measured.

In all tests it was possible that the contamination of the surfaces of the steam dome and steam lines could lead to bias in the SORV condensate results, if the contamination was only slowly removed by the dry SORV steam flow. In most tests steady-state operation before the model boiler was dosed with lithium hydroxide ensured that the steam surfaces were not contaminated and no effect was seen. It did appear, however, when transients released relatively large amounts of tracer into the steam spaces and was observed during the 100% power moisture carryover test and in all the low level tests.

With samples at sub-ppb levels, there was the possibility that part of the sample could be lost by plateout onto the walls of the sample bottles. Plateout was minimized by analyzing the SORV samples within 2 to 3 hours, but tests also showed that plateout was insignificant on storage over 24 hours.

The final factor which can affect the SORV condensate results is the contribution of volatility to the measured carryover. For the tracers used in the tests this can be derived from the data reported by Stephan and Kuske (1), extrapolated to the conditions used in individual tests. The estimated values are given in Table 7-1 as a function of tracer concentration at the secondary side operating pressures used in the tests.

Although the calculated volatities are subject to some uncertainty, the values indicate that volatility need only be considered at normal operating pressures. For such conditions significant contributions are only predicted when the lithium concentration exceeds 40 ppm or when the potassium concentration exceeds 300 ppm, at which levels the the volativity would be predicted to be comparable to the carryover measured in many of the tests.

In summary, the analytical techniques were capable of measuring down to 0.2 ppb lithium or potassium, with a precision of ± 0.2 ppb and without bias due to interference effects, contamination or plateout. However, at the tracer levels generally used in the tests, the volatities of both lithium and potassium hydroxide are predicted to be comparable with the measured carryover.

High Concentration Samples

For these samples the important analytical aspects are whether the samples were representative of the conditions existing within the model boiler and whether the results obtained by analysis after dilution are consistent either with the mass of tracer added to the system or to the conductivities measured on the undiluted sample streams.

For primary loop samples representative sampling can be assumed at all times, but for the model boiler representative sampling can only be assumed when single-phase conditions, either water or steam, existed in the vicinity of the sample take-off point. Generally, this applied at normal or high water level only. At other times, under two-phase conditions, representative sampling cannot be expected as the sample points were not designed for isokinetic sampling under the test conditions. For such two-phase conditions the results require additional data before they can be scaled to true model boiler concentrations.

A comparison between the observed conductivities and those calculated from the analytical results is given in Table 7-2. From this it is clear that good agreement was only obtained in seven of the tests. In the remaining cases the conductivities and, when measured, the pHs were low. Since mass balance considerations, see Section 7-2, indicate that the analytical results were generally correct, the conductivities suggest that there were unidentified acidic impurities present in the water which would reduce the pH and hence, the conductivity. These impurities are not expected to have influenced carryover, but could have had some influence on volatility. In general, however, since the results show very little carryover, any effect due to other volatile salts is considered to be negligible.

7-2. ASSESSMENT OF MODEL BOILER WATER CONCENTRATIONS

For each test the lithium and potassium concentrations in MB-2 are a function of the amounts dissolved in the model boiler water and the mass of water present. If no hideout occurs, the masses of lithium and potassium can be calculated from the amounts added, summarized in Table 7-3, after correcting for losses via the SORV steam and the model boiler sample lines, while the mass of water can be estimated from the data given in Section 6.0. When the sample lines are expected to be taking representative liquid samples, these estimates provide a means of confirming that they are giving correct readings. At other times they provide a means of calculating the true concentrations in the model boiler and, for those tests involving blowdown to low water level, they enable estimates to be made of the mass of lithium remaining in the model boiler at the end of the blowdown phase. Finally, at low level the mass balances can indicate whether hideout was occurring.

At low power and at normal or high water level, themocouple readings indicate that both the S-1 and IKP-4 samples are taken from subcooled regions of MB-2 and they should, therefore, provide representative samples of model boiler water. To confirm this, it is simpler to use the amounts of tracer added and the measured concentrations to calculate the mass of water present in the model boiler, rather than to calculate the concentrations, since the liquid masses can be compared with those given in Section 6.0 and with independent estimates using the NOTRUMP code (2). These estimated masses are summarized in Table 7-4.

Of the tests performed, ten were carried out at normal operating pressures (1050 to 1080 psia), normal water levels and at low power (2 to 10% steam flow). For these tests, the estimated masses from the initial lithium injection are generally in the range of 934 to 1099 lbm. These values may be compared with that estimated in Section 6 of 1152 lbm and with the values predicted using the NOTRUMP code, which ranged from 980 to 1038 lbm for the test conditions appropriate to Test 1, both with and without an SGTR flow.

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From the agreement between the three methods of estimating mass it is clear that, normally, the observed concentrations were consistent with the masses of lithium hydroxide injected into the model boiler and that both the S-1 and IKP-4 sample lines were taking representative samples. At later stages in the tests the estimates of liquid mass are complicated by changes in level during the tests and by the loss of liquid into the void space when the dryer was flooded. As a result, the estimated masses derived from the lithium and potassium results may be inaccurate. However, generally similar estimates were obtained using either the amount of lithium or the amount of potassium present.

In Tests 3, 4 and 14 water level was maintained throughout the tests and here mass can be estimated using both the lithium and the potassium data and at either the start or end of the tests. For the three tests all estimates of liquid mass lie in the range of 1120 to 1300 lbm, somewhat higher than the NOTRUMP estimate of ~ 1100 lbm. From the consistency, however, the mass estimates are probably correct and again they indicate that the sample lines were giving representative results. Moreover, the results also show that the calculated SGTR flow rates, used to calculated the mass of potassium injected into the model boiler, are essentially correct, and that there were no significant losses due to hideout. In Test 5 water level again increased during the test, but without flooding the secondary dryers. In this test the masses calculated from the lithium concentrations are low, both when compared with the estimate derived from the SGTR flow and with that estimated by the NOTRUMP code, 1280 lbm. This suggests some loss of lithium hydroxide during dosing, but, nevertheless, the measured concentrations were expected to be accurate.

In the two tests at 100% power, only the results from the S-1 sample line can be used to estimate mass, since two-phase conditions existed at the IKP-4 sample point in the tube bundle. Using the S-1 results the two tests give similar estimates of mass, 839 and 850 lbm, both of which are significantly higher that those calculated using the NOTRUMP code, 594 lbm. While the differences may, in part, be due to the rapid loss of lithium by hideout that

579

occurred at full power, the results possibly suggest that some level of voidage might have existed in the upper downcomer barrel, even though, nominally, the S-1 sample point lay below the downcomer water level. Voidage would, of course, result in lower observed sample line concentrations, since the steam would contain very little lithium, and lead to high estimates of liquid mass in the model boiler.

As soon as the water level is reduced, the S-1 sample point uncovers and it will sample a two-phase mixture. Concurrently, bundle thermocouple data recorded during blowdown (see Tests 8, 9 and 14) plus the density distributions within the model boiler, both indicate that the IKP-4 and the blowdown sample points also sample two-phase mixtures. Thus, as soon as the level is reduced, none of the sample lines can be assumed to be taking representative samples and they can no longer be relied upon to give absolute results. However, since the steam sampled will contain very low tracer concentrations, the relative concentrations measured should still be representative of the values in the model boiler water. For tests at low level, therefore, if suitable scaling factors can be calculated, they can be used to derive the absolute model boiler concentrations from those measured using the S-1 and IKP-4 sample lines.

For Test 2 corrected concentrations can be derived from either the lithium or potassium masses in the model boiler, but for most of the remaining tests at low level only the potassium mass can be used, since lithium was lost during the blowdown phases of the tests. In addition, in Tests 8, 9, 15 and 16 only the results at 160 and 280 in. can be used, since the data indicate that hideout occurred at lower levels (see below). Although lithium was lost during blowdown, the amounts remaining in the model boiler can be calculated from the mass of potassium injected during each SGTR and using the measured lithium and potassium concentrations, and then correcting for losses via the SORV steam and sample lines. The calculated concentrations and lithium masses are summarized in Tables 7-5 and 7-6.

In Test 2 the calculated concentrations, based on the masses of lithium and potassium present, gave almost identical lithium to potassium ratios to those measured using either the S-1 or IKP-4 sample lines. As expected, however, the measured concentrations were low and the scaling factors required to correct for dilution by steam during sampling ranged from 1.08 to 1.98 (see Table 7-5). Again, as expected, the scaling factors are greater for the S-1 sample line and increase as the level is reduced. As in other tests at normal water level, the agreement observed confirms the accuracy of the SGTR flows and that hideout did not occur to any significant extent.

For the remaining tests the accuracy of the calculated concentrations cannot be checked directly, but here, the consistency obtained in the estimates of the lithium mass present at the end of blowdown would indicate that the calculated results are essentially correct. Again, as expected, the scaling factors increase on reducing water level and are greater for the S-1 sample line. However, from test to test these scaling factors vary significantly, again confirming that the sample lines cannot be expected to give reproducible sampling of a two-phase mixture. If the calculated lithium masses at the end of the blowdown phase are compared, it may be seen that good agreement was obtained for either sample line in the top break tests (Tests 8 and 15) but that in the bottom break tests (Tests 9 and 16) the mass estimated using the IKP-4 line was systematically greater. This suggests uniform mixing at the sample points in the top break tests, but incomplete mixing at the IKP-4 sample point in the bottom break tests.

At lower water levels in Tests 8, 9, 15 and 16, below about 130 in., when there was no recirculation within the model boiler, the data indicate that hideout occurred via the transfer of tracer chemical onto the dry surfaces of the tube bundle. Five observations point to the occurrence of hideout. These are,

(i) During steady-state operation (with no SGTR flow) the measured model boiler concentrations fell steadily. Notably, this was seen after blowdown and after the SGTRs in the later tests with the dryers bypassed.

5021

(ii) In the SGTRs at ~ 60 in. the measured concentrations on the IKP-4 sample line, from the pool of boiling water, are very much less for top break tests (8 and 12 ppm) than for bottom break tests (380 and 390 ppm). This suggests that most of the potassium injected during the top break SGTRs was lost onto the surfaces of the tube bundle.

(iii) On raising water level following the SGTRs at ~ 60 in. in the two tests with the dryers bypassed, when steady state conditions had been maintained for 20 minutes after the SGTR, both the lithium and potassium concentrations increased. Here, this would indicate redissolution of the tracers as the water level was raised.

(iv) In the absence of hideout the ratios of lithium to potassium would be expected to be similar, either when calculated from the mass present or from the measured concentrations. A comparison of these ratios, given in Table 7-7, shows that this was not so and, in particular at ~ 60 in., the ratios differed by up to one order of magnitude. Again, this points to hideout during the tests.

(v) In the top break SGTR tests at ~ 60 in., initiation of the break flow caused a spike of lithium release, but not of potassium. Probably, this was derived from lithium hydroxide deposited on the dry surfaces before the SGTR was initiated.

From the above considerations, the low level tests at 60 and 100 in. water level were associated with significant amounts of hideout. Because of this, it is not generally possible to estimate the concentrations present in the liquid phase, since the amounts lost by hideout cannot be determined. The total masses in the model boiler can be calculated, however, as can the concentrations at the end of blowdown before any lithium was lost into the tube bundle. Estimates of these values are given in Table 7-7.

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In the final test of this group, Test 14, blowdown occurred between the two SGTR phases and both lithium and potassium were lost during blowdown. Hence,the amounts remaining after blowdown are uncertain. Fortunately, for these test conditions the IKP-4 sample line results show that hideout did not occur, since the lithium concentrations decayed only by the amounts predicted by sampling losses. The results at 100 in. can, therefore, be analyzed and the mass present calculated on the basis of the mass of potassium added during the final SGTR and of the observed increase in potassium concentration. The masses can then be used to calculate the true concentrations in the model boiler. As expected, the calculations show that two-phase conditions existed at the IKP-4 sample point and that a scaling factor of ~ 1.3 is required to correct the measured concentrations. These results are summarized in Table 7-8.

7-3. CARRYOVER AND BYPASSING

During a potential steam generator fault involving a coincident SGTR and SORV, moisture released via the SORV steam can originate either from the bulk steam generator water or from unmixed primary coolant issuing from the SGTR break site. The former is referred to as moisture carryover, while the latter can be defined as primary coolant bypassing. Both carryover and bypassing can occur either as steady-state processes or as transient releases, and it should be noted that primary coolant which has mixed with the bulk steam generator water can be released by moisture carryover as well as by bypassing.

Steady-State Definitions

In the present series of tests lithium was added to the model boiler as the secondary tracer, and moisture carryover can be determined directly from the concentrations of lithium in the SORV condensate, $[\mathrm{Li}]_{SORV}$, and in the model boiler water, $[\mathrm{Li}]_{MB-2}$. Carryover is defined as,

$$\text{Carryover} = \frac{\text{mass of water discharged}}{\text{total mass discharged}} \times 100\%$$

$$= \frac{m_{water}}{m_{water} + m_{steam}} \times 100\% \qquad (7\text{-}1)$$

However, since $[Li]_{SORV} = \frac{[Li]_{MB-2}\, m_{water}}{m_{water} + m_{steam}}$,

Carryover can also be defined as,

$$\text{Carryover} = \frac{[Li]_{SORV}}{[Li]_{MB-2}} \times 100\% \qquad (7\text{-}2)$$

Potassium was used as the primary tracer and will enter the model boiler via the SGTR break. If there is no bypassing, and the injected primary coolant mixes uniformly with the model boiler water, carryover can also be determined from the equivalent potassium concentrations.

$$\text{Carryover} = \frac{[K]_{SORV}}{[K]_{MB-2}} \times 100\% \qquad (7\text{-}3)$$

Since the lithium concentration in the model boiler water remains approximately constant during the tests, while the potassium concentration increases throughout the SGTR injection, in theory similar behavior in concentration should be observed in the SORV condensate. In practice, the measured concentrations were so low that these trends could not be detected. Here, therefore, only upper limits for carryover based on potassium data have been calculated. These use the maximum concentrations in the model boiler at the end of each SGTR injection.

Bypassing can be defined as that fraction of the mass of primary coolant entering the model boiler, via the SGTR break, which escapes directly in the SORV steam. If bypassing occurs, the potassium concentrations measured in the SORV steam will be a combination of the contributions due to bypassing and to moisture carryover. It should consist of a constant contribution due to bypassing plus an increasing contribution due to moisture carryover. Since, in practice, the observed concentrations were very low, the individual contributions cannot be separated and, again, here only upper limits for bypassing (i.e., total primary carryover) have been calculated. These assume that all the potassium in the SORV condensate was due to bypassing. Thus,

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$$\text{Upper Limit for Bypassing} = \frac{\text{Mass leaving MB-2}}{\text{Mass entering MB-2}} \times 100\%$$

$$= \frac{[K]_{SORV}\, W_{SORV}}{[K]_p\, W_{SGTR}} \times 100\% \qquad (7\text{-}4)$$

where W_{SORV} and W_{SGTR} are the SORV steam and SGTR flow rates and $[K]_p$ is the concentration of potassium in the primary loop.

Transient Release Definitions

In a number of the tests, perturbations in operating conditions caused transient increases in the amount of lithium or potassium carried over into the SORV steam. Usually, the levels observed were not sustained and decayed exponentially towards the steady-state values. These releases have been assessed by first estimating the total mass of tracer released, M^{Li}_{SORV}, and then comparing this with the calculated mass in the model boiler, M^{Li}_{MB-2}, at the start of the perturbation.

$$\text{Carryover} = \frac{M^{Li}_{SORV}}{M^{Li}_{MB-2}} \times 100\% \qquad (7\text{-}5)$$

For potassium, transient releases can originate from the bulk liquid or from bypassing. Of these, bypassing could only be identified unambiguously at the start of an SGTR, when potassium was absent from the bulk liquid phase. For these transients, upper limits for the fraction of primary coolant released by bypassing can be calculated by comparing the mass of potassium released via the SORV steam, M^{K}_{SORV}, and the mass of potassium injected into the model boiler over the period of the perturbation, where Q_{SGTR} is the total quantity of primary coolant injected. Thus,

$$\text{Upper Limit for Bypassing} = \frac{M^{K}_{SORV}}{[K]_p\, Q_{SGTR}} \times 100\% \qquad (7\text{-}6)$$

In most instances the perturbations which produced transient releases probably occurred over relatively short periods, typically 20 to 30 seconds at the start of the SGTR break flow or up to 60 seconds on opening the safety relief valve. Generally, however, these short perturbation caused much longer transients in the SORV condensate, typically 10 to 15 minutes. In calculating transient carryover, this aspect will not influence the calculated result, but for bypassing, the values estimated will be critically dependent on the time period chosen for the perturbation and can only be used with reference to this assumed time. Since this approach can introduce uncertainties in assessing transient bypassing, the release can be reexpressed in terms of the time period over which 100% bypass release can be assumed to occur, an approach which eliminates the need to specify a perturbation time period.

7-3-1. Carryover and Bypassing at Normal or High Water Level

Under steady-state conditions the measured SORV condensate concentrations were very low and usually were either not detectable or close to the limits of detection of the analytical methods. Carryover and bypassing levels calculated from those values were also low, generally lying in the range of 0.0004% to 0.002%. These results are summarized in Tables 7-9 and 7-10.

Examination of Table 7-9 shows that the results were similar for all tests and that comparable values were estimated using either lithium or potassium data. In most instances the apparent range in the results arises from the variation in model boiler concentrations and was not a real effect. From the data at higher dosing levels, the true carryover level was very low and of the order of 0.0005% or less. As noted in Section 7-1, volatility should not contribute to the measured carryover in Tests 3, 4, 5 and 14, but the predicted volatility could account for most of the observed carryover in the remaining tests. In the two 100% power tests the measured carryover was significantly higher than in other tests. This will remain correct, even if the model boiler concentrations were higher than measured (see Section 7-2) and if increased volatility corrections are made.

In most tests, variations in water level did not have any significant effect on the measured carryover. These span the range 130 in. to 495 in. under Test 1 type conditions, and up to ~ 520 in. at lower secondary temperatures and pressures. At 100% power raising the level up to the dryer had no effect, but carryover increased to 10 to 20% on flooding the dryers. With the dryer bypassed no change in carryover was detected, except again at 100% power when water level was increased above normal level.

Although there was little evidence for primary coolant bypassing, upper limits can be calculated for each test. These show that any bypassing was very low and comparable to the level for carryover. Again, the values mainly reflect the dosing levels used, rather than definitive values. Even though the evidence for bypassing was slight, the sustained higher levels of potassium seen in Tests 5 and 14 would suggest that bypassing did occur to a very small extent in these tests. It may also have occurred in Test 4. It is perhaps significant that evidence for bypassing was only seen in tests at lower secondary temperatures and pressures. Possibly this was related to the greater volumes of steam produced when the primary flow flashed under these conditions. Associated with the small degree of bypassing in Test 14, carryover, as measured by the lithium concentration, also increased while there was an SGTR break flow.

In a number of tests, perturbations to steady-state conditions caused transient releases. At these water levels, they occurred in the overfill tests (Tests 10 and 11), in the full transient test (Test 12), and in Tests 1, 4 and 14. These transient releases are summarized in Tables 7-11.

In the two overfill tests, Tests 10 and 11, each pressure relief cycle caused a transient release. In Test 10 these could not be resolved fully due to the method of sampling and are not analyzed further. In Test 11, each pressure relief cycle lasted for 75 or 80 seconds and caused an SORV condensate flow for about 150 seconds. During this time the tracers gave high initial concentrations, which decayed exponentially to lower values. During the first two cycles the initial concentrations were relatively low and the decay slow, while in the final two cycles the initial concentrations were high and the decay rapid. In the intermediate cycles both types of behavior appeared to be present.

For the four cycles where sufficient data exist, the observed concentrations can be expressed as,

Cycle 1: Lithium - $C_{Li} = 4e^{-0.86t}$
Potassium - $C_K = 19e^{-1.1t}$
Cycle 2: Lithium - $C_{Li} = 28e^{-1.1t}$
Potassium - $C_K = 11.5e^{-0.72t}$
Cycle 5: Lithium - $C_{Li} = 300e^{-0.098t}$
Potassium - $C_K = 530e^{-0.098t}$
Cycle 6: Lithium - $C_{Li} = 1050e^{-0.149t}$
Potassium - $C_K = 4600e^{-0.149t}$

where concentration is expressed in ppb and time in seconds. If we integrate over infinite time and use an average SORV steam flow rate of 1.97 lbm/sec. (0.895 kg/sec), we obtain estimates of the total mass released. These are summarized in Table 7-11.

It is difficult to compare all six pressure relief cycles on a quantitative basis, due to the difficulty in analyzing the intermediate cycles and because of the uncertainty in the actual mass of water available for release, when part of the total inventory was being lost continually into the void space of the model boiler. However, it is clear from the data that the mass released generally increased progressively from cycle to cycle as the water level was raised. Further, if the calculated releases given in Table 7-11 are compared, it may be seen that similar quantities of both lithium and potassium were released during cycles 5 and 6, but that in cycles 1 and, possibly, 2, greater percentages of potassium were released than lithium. A similar conclusion can also be drawn from the data for all six cycles, if the observed concentrations after 30 seconds are compared with the corresponding concentrations in the model boiler. These are given in Table 7-12. Both comparisons would indicate that the release in cycles 3 to 6 was of model boiler water alone and that there was no contribution from bypassing. In the initial cycles the data indicate that some bypassing occurred in cycle 1 and possibly also in cycle 2. If the water levels are compared, it may be seen that cycle 1 occurred at about 502 in., whereas all other cycles occurred at or above 514 in., the level of the entrance to the dryer.

The transients observed in the remaining tests, Tests 1, 4, 12 and 14, were detected over longer time periods, 10 to 20 minutes, and at times when samples were being collected at 5 minute intervals. In these cases the quantities released were estimated directly from the plotted results and from the corresponding SORV steam flow rates. The transients fall into two groups, those seen in Test 12, the full SORV transient with a top break SGTR, and those seen in the remaining bottom break SGTR tests at the start of the SGTR break flows.

In Test 12, both identifiable transients occurred when the SORV lines were opened, in one case to relieve pressure, in the other to increase flow from 2% to 10%. Both were, therefore, similar events to those described above for Test 11, but here they occured at lower water levels of about 440 in. and 480 in., respectively. In both cases, as in Test 11, cycle 1, the results indicate that some bypassing occurred. Although the transients were observed over a period of about 12.5 minutes, the SORV flow (Figure 5-350) shows that the initiating perturbation occurred over much shorter time scales. From the data these are estimated to have lasted of the order of 60 seconds. However, for ease of direct comparison with Test 11, cycles 1 and 2, here, upper limits for bypassing are calculated on the basis of an 80 second perturbation. On this basis the results indicate that there was about 0.5% bypassing in each transient. This is equivalent to 100% primary coolant bypassing over a period of 0.4 seconds. Because of their similarity, the four transients, from Test 12 and from Test 11 (cycles 1 and 2), should provide a basis for estimating releases caused by the operation of a safety relief valve at normal water levels.

In the three bottom break tests small transients, lasting for 15 to 20 minutes, were observed when the SGTR break flow commenced. Since potassium was absent from the model boiler water before the SGTR flow was initiated,

529

these transients must be due to bypassing. Again, as noted above, the initiating perturbations for these transients are believed to have occurred over much shorter periods and probably originate from the surge which occurred on initiating the SGTR flow. From the data these surges lasted for 20 to 30 seconds. Here, we have assumed a fixed period of 25 seconds for estimating bypass in each transient. From Table 7-11, the calculated levels of bypassing in each case are predicted to be small and would not be expected to dominate the total release in actual faults.

7-3-2. Carryover and Bypassing at Low Water Level

Low water levels were investigated in eight tests. Principally, the conditions explored were blowdown or boildown, SGTRs at very low water level when there was no recirculation in the model boiler, and SGTRs at intermediate water levels with recirculation maintained. Generally, these tests were dominated by transient releases, which were related to the specific operating conditions in each test. These conditions and the observed releases are described below, while the results are summarized in Tables 7-13 to 7-15.

Blowdown and Boildown

The effect of blowdown or boildown was examined in all low level tests. Of these, four were carried out under essentially identical conditions and will be considered in detail.

In these tests, Tests 8, 9, 15 and 16, level was reduced by blowdown from normal level, 442.5 in., to about 50 in. while steaming at about 1.9 lbm/sec. Typically, the primary inlet temperature, T_{hot}, was 580°F (304°C), the primary flow rate 91 to 95 lbm/sec., the secondary pressure 1080 psia and the saturation temperature 552 to 556°F (~ 290°C). At normal water level the downcomer flow rates indicated a circulation ratio of about 17. This fell to 5 by a downcomer water level of about 180 in., after which it remained constant. Since the analytical results obtained on the S-1 sample line show that recirculation did not cease until the level had fallen to about 130 in., the downcomer flow rates probably were inaccurate at low level (when the

530

apparent circulation ratio should equal unity, since the auxiliary feed flow should equal the SORV steam flow rate). As soon as the water level was reduced, thermocouple readings showed that the subcooled region at the base of the tube bundle rose to saturation temperatures and that two-phase conditions existed throughout the tube bundle. These conditions persisted until recirculation collapsed, when superheat was developed in the upper part of the tube bundle (observed at both 195 and 260 in.). Eventually the steam in this region of the tube bundle developed up to 20°F (11°C) superheat (Figures 5-101, 5-103, 5-211, 5-213, 5-401, 5-402, 5-488 and 5-489). Even though superheat was developed in the tube bundle, thermocouples in the riser at 363 in. showed that saturated conditions were maintained at this location at all times. Finally, when water level had fallen below 100 in., both the saturation temperature and secondary pressure fell, as there was no longer sufficient heat transfer surface in the tube bundle to maintain secondary pressure.

When water level is reduced by blowdown, it might be expected that the model boiler water concentrations would remain constant. In practice this does not occur, since the blowdown take-off point lies in the path of the return downcomer flows and removes the downcomer water and not bulk water. In the initial stages of blowdown the downcomer water is similar in composition to the bulk model boiler water, but as level is reduced and the circulation ratio falls, the downcomer water becomes progressively more like the undosed auxiliary feed water that is being added to the downcomer at all times. Thus, blowdown involves the removal of water, but not of the corresponding amount of chemical tracers and the result should be to concentrate the latter in the bulk water. In the tests considered here, the predicted concentrating effect could not be observed directly, since the sample points saw progressively higher levels of voidage, but it was observed in the similar test, Test 14 (T-2067), and it can be demonstrated via the mass balances outlined in Section 7.2 The latter indicate that the model boiler water concentrated by factors of the order of 2 to 3 in this series of tests.

The observed carryover can be split into three phases, namely steady-state values with recirculation maintained (at levels above 130 in.), transient releases as recirculation within the model boiler collapsed, and steady-state

531

values at levels between 50 and 130 in. when there was no recirculation. During the initial stages of blowdown, when recirculation was maintained within the model boiler and at levels between 442.5 and 130 in., carryover was very low and not significantly different from that at normal water level, see Tables 7-11 and 7-13. Neither was there any evidence for an increase in carryover as concentrations increased within the model boiler. At about 130 in., when recirculation collapsed, carryover increased and a transient release of variable character and duration was observed in all four tests. In two cases carryover increased over 5 minutes and then decayed exponentially over a further 10 minutes, but in the remaining tests the transient was more variable and of longer duration. Probably these variations were related to the particular rates of reduction in water level employed in each test. If the total masses released are compared with the masses present at the end of blowdown, Table 7-16, the quantities released were similar in all tests and all lie in the range of 0.4 to 1.3%. Once level had been stabilized at about 50 in., and when there was no recirculation in the model boiler, carryover rapidly increased to new steady-state values which were about one order of magnitude higher than those seen earlier, Table 7-13. These levels are still significantly higher, even when account is taken of the increased volatility predicted at the higher concentrations following blowdown, see Table 7-1. In the 70 to 80 minutes operation before the initial SGTR phase, no effect due to loss of tracer by hideout was observed. At all stages, there were no identifiable effects due to the bypassing of the dryer in the repeat tests.

Water level was reduced to very low levels in three further tests. In two of these, Tests 10 and 11, level was reduced by boildown (with a concurrent SGTR flow in Test 11), while in Test 14 level was reduced by blowdown. In Tests 10 and 11 conditions were similar to those above, but with a much reduced primary flow rate. In Test 14, at lower temperature and pressure, they were, T_{hot} 470°F (233°C), primary flow 13 lbm/sec, secondary pressure ~ 430°F (221°C) and SORV steam flow, 0.5 lbm/sec. In these three tests blowdown or boildown did not cause the same transient release when recirculation collapsed as was seen in the tests described above. Further, only in Test 11 was there any indication for an increase in carryover of very low level, Table 7-13. The differences in behavior between these sets of tests would appear to be associated with the amount of heat transfer available in the tube bundle and,

532

possibly also, with the lower SORV steam flow rates. This was reflected in the amount of superheat generated in the tube bundle, which here was about 9°F (5°C) maximum in Test 11 (Figures 5-333 and 5-334) and 3°F (2°C) in Test 14 (Figures 5-383 and 5-384).

In Test 2 (T-1958), two small transient releases also coincide with rapid reductions in level due to boildown. In both cases the reductions in water level were from 250 in. to about 200 in. and, hence, took place with a fairly high circulation ratio in the model boiler. In both cases the quantities released were small, Table 7-16.

SGTRs or Other Events at Very Low Water Levels

The effects of SGTRs at very low water levels were studied in five tests, Tests 8, 9, 14, 15 and 16. In addition, the effect of increasing the SORV steam flow rate, as in a pressure relief cycle, was examined in Test 11. The results are summarized in Tables 7-13 to 7-15.

In the main group of four tests, Tests 8, 9, 15 and 16, SGTRs were carried out at water levels of about 60 in. and 104 in., with the break location at either the top or bottom of the tube bundle and with the dryer either in service or bypassed (Figures 5-192, 5-302, 5-475 and 5-562). Since no effect due to bypassing the dryer could be identified, the following description deals only with the effects due to the break location and considers tests with or without the dryers bypassed as equivalent. For each test the conditions were similar, the only differences being an increase in T_{hot} at the lower SGTR level, 594°F (312°C) versus 580°F (304°C). At 60 in. up to 16°F (10°C) superheat was observed in the upper part of the tube bundle (at 195 and 260 in.; Figures 5-121, 5-123, 5-232, 5-234, 5-416, 5-417, 5-503 and 5-504), but at 100 in. superheat was only seen at the very top of the bundle at 260 in. At this level the superheat was about 5°F (2.5°C) before the SGTRs and during the bottom break SGTRs (Figures 5-253 and 5-519), but it was reduced to zero during the top break tests (Figures 5-142 and 5-432). In all tests the concentrations observed in the SORV condensate were dominated by large transient releases. These occurred at the start of each SGTR and during the associated level changes from 60 to 100 in. and from 100 to 150 in.

Generally, the SORV condensate concentrations fell only slowly in each transient, so that steady-state conditions were never fully established.

At 60 in. the initial SGTR produced a marked difference in behavior depending on whether the break was located at the top or bottom of the tube bundle. In both top break tests, initiating the SGTR break flow caused a large transient release of lithium, but no corresponding release of potassium, while in the bottom break tests there were no large releases of either lithium or potassium. In one bottom break test there was a small release of both potassium and lithium at the start of the break flow, but the amounts released were small when compared with the lithium released in the top break tests. As the SGTRs proceeded, the potassium carryover increased steadily in all the tests, in parallel with the total amount added to the model boiler, and in the repeat tests this carryover level was maintained in steady-state operations after the break flow had ceased. Apart from the small release seen in one test, there was no evidence that bypassing occurred.

At first sight these results are difficult to explain, for if the lithium had remained in the boiling pool at the bottom of the tube bundle it might be expected that it would only be released in a bottom break test, and not in a top break test. Further, if the releases were caused by initiating the break flows, then corresponding releases of potassium would be seen. The results may be explained, however, if it is assumed that the lithium was not restricted to the boiling pool, but that it was distributed throughout the tube bundle and that it had accumulated as deposits on the dry surfaces in the upper part of the bundle. A top break SGTR will now result in the primary coolant, at saturation temperature after it has flashed, draining onto the tube bundle where it will boil and release these deposits as fine particulates or concentrated droplets. Evidence for this behavior can be seen in Figure 5-121 and 5-416, the thermocouple traces at 260 in. in Tests 8 (T-1976) and 15 (T-2051). The absence of a corresponding release in the bottom break tests may now be explained simply as due to the lack of access to these dry deposits. As outlined in Section 7-2, there are other indications that hideout of this type occurred at very low water level, particularly the observations that the potassium injected in top break tests did not reach the

534

boiling pool and that in steady-state operation after the SGTR the measured potassium concentrations on the IKP-4 sample line fell rapidly.

If this interpretation of the results is correct, then quantitative estimates of the amounts released must be treated with caution as they will now depend on the quantity of dry deposit exposed to the break flow, which in turn will depend on the prior operational history when it will have accumulated. In the present series of tests this period was similar in all cases, 70 to 80 minutes, and resulted in the loss of up to 8% of the total lithium inventory in top break tests, but very little in the bottom break tests. For the same reason, estimates of steady-state carryover and bypassing cannot strictly be made, since the true concentrations in the boiling pool are unknown, as are contributions due to other processes occurring in the tube bundle. The estimates given in Tables 7-13 and 7-14 must, therefore, also be treated with caution, but they suggest that both carryover and bypassing were low.

At the second SGTR level, 104 in., both lithium and potassium were present before the SGTR flow commenced and both may be expected to have been present in any deposits on the dry surfaces of the tube bundle. At this level all tests gave a similar result, with the release being dominated by transients of both lithium and potassium. Although variable, the releases, Table 7-15, were similar in magnitude to those seen at 60 in. and were relatively similar for both tracers. Again, this suggests release from dry deposits, with no dominant contribution due to bypassing. In each test the measured lithium concentrations decayed until water level was raised to 150 inches. A similar behavior was not normally seen with potassium, where the measured concentration remained high even after the SGTR flow was halted. This would indicate some type of carryover behavior rather than bypassing, but again, it is difficult to define these values accurately. As at 60 in., however, steady-state estimates suggest low levels of both carryover and bypassing.

On raising water level at the end of each SGTR phase, further large transient releases of both lithium and potassium occurred in all tests. In each case the transients were similar to those seen in the SGTRs and were of similar magnitude. As with the SGTRs, there were appreciable variations in the quantities released from test to test and in the relative amounts of lithium and potassium. Generally, such variation might be expected if the release was from deposits in the tube bundle, since the quantities released would depend on the prior operational history and on the variation in distribution caused by the alternative break locations. In these level changes it is probable that the releases were caused by the rewetting of these dry surfaces as level was raised. Consistent with this interpretation was the observation that the measured concentrations on the IKP-4 sample line from the boiling pool at the base of the tube bundle increased when level was raised, rather than decreased as expected due to dilution. This would suggest redissolution of deposits as the level was raised.

In all transient releases the SORV concentrations fell exponentially to lower concentrations over prolonged periods. This was particularly apparent after levels had been raised to 160 in., when concentrations continued decaying for 1 to 2 hours after the level change. This slow recovery would indicate that the tracers were trapped in crevices within the model boiler from which they were only slowly leached out. The sites for these crevices are uncertain and they could lie in the steam spaces of the model boiler or in the support plate crevices of the tube bundle. As, however, a uniform distribution of the tracers in the model boiler water was reestablished rapidly once recirculation had been established, the slow decay seen after recirculation was reestablished at 150 in. suggests that crevices in the steam spaces were responsible.

A similar test to those described above, but at lower temperatures and pressure, was carried out in Test 14, where the second stage of the test involved a bottom break SGTR at a water level of 102.5 in. In this case, however, the SGTR was carried out only 18 minutes after completing blowdown and when the measured concentrations on the IKP-4 sample line suggested that mass was not being lost into the tube bundle. As in the previous tests at this water level, both lithium and potassium were present before the SGTR break flow commenced and, again, initiating the SGTR break flow caused transient releases of both tracers (Figure 5-391). In this example, however, the total quantities released were very much less, since hideout was not taking place, and there was a much greater quantity of potassium released than lithium. This then indicates that the release was mainly due to bypassing and

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that it parallels the behavior seen at normal water level in this particular test. Estimated as bypass, and assuming a 25-second initiation period as at normal water level, the bypass fraction is estimated at ~ 3% , approximately 30 times that seen at normal water level. Again, as at normal water level, bypassing was associated with a small release of bulk model boiler water. After the initial release, the measured SORV condensate concentrations fell to very low levels. Based on these values, both steady-state carryover and bypassing were low, Table 7-13 and 7-14, and were similar in magnitude to that seen at normal water level. These levels were significantly less than the carryover seen in the other tests at these low water levels. Possibly this difference is related to the lower steam flow and the absence of hideout in this particular test.

In the final low level test, Test 11, the effect of increasing the steam flow from 2% to 10% was examined (Figure 5-337). As this period of increased flow lasted for 72 seconds, it was almost directly comparable with the pressure relief cycles carried out at earlier stages in the test, but carried out at a level of 23 in. As in the other pressure relief cycles, the top break SGTR flow was still in operation during the transient. The transient caused a relatively large release of both lithium and potassium, with approximately three times the amount of potassium released as lithium. Since there was no reason to expect an uneven distribution of tracers within the model boiler or an uneven release due to carryover, the result would suggest that ~ 65% of the potassium release was due to bypassing. On this basis, over a 72-second injection period, bypassing was ~ 44%, the highest level seen in any test.

SGTRs and Other Events at Intermediate Water Levels

Five tests were carried out at water levels between 150 in. and 290 in., when recirculation was still being maintained in the model boiler. Four of these were continuations of those described above, Tests 8, 9, 15 and 16, while the additional test was Test 2 (T-1958) carried out under essentially identical conditions. In the main group of four tests the overall carryover was dominated by the decay of the SORV condensate concentrations following the transient releases when water level was raised to 160 in. As this decay extended throughout the remainder of each test, steady state-levels could not be estimated and only transient releases are considered. The results are given in Tables 7-13, 7-14 and 7-16.

In Tests 8, 9, 15 and 16, SGTRs were carried out at two water levels of 160 in. and 285 in., separated by a single change in water level (Figures 5-194, 5-304, 5-477 and 5-564). In most cases, initiating the SGTR flow or raising water level caused small transient releases, which were detected above the general background concentrations. However, while most events caused potassium releases, only three events caused a corresponding lithium release. In the SGTR phases, these differences could suggest that bypassing occurred, but similar variations seen in the level change plus the small quantities released suggest that the differences mainly are due to the difficulties in identifying and estimating the amounts released. If the tests with or without the dryer are compared, transient releases are seen more frequently with the dryer bypassed. If this was caused by bypassing the dryer, then it was the only occasion when any effect was detected, other that at 100% power and at high water level.

The difficulties caused by background carryover from earlier phases of the tests did not affect Test 2, and in this test steady-state carryover estimates could be made. In the initial phase of this test, carried out at 240 to 280 in., carryover was very low and was comparable to that seen at normal water level. At lower water level, 190 to 205 in., carryover increased and was more variable, but still was of a similar magnitude to that seen at normal water level. Upper limits for bypassing at both levels were also small and there was no evidence for any significant level of bypassing. As described earlier, transient releases were seen on two occasions. The first of these transients occurred when the SGTR break flow was initiated, but it also coincided with a rapid reduction in level by boildown. This transient was probably caused by the break flow surge and gave a similar level of bypassing to the similar transients in Tests 1, 4 and 14. The second transient also coincided with a rapid change in water level and, in this case, was clearly due to this event. In contrast with the earlier transient, there was no evidence for bypassing on this occasion.

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7-4. ASSESSMENT OF TEST RESULTS

The prime objective of the test program was to measure moisture carryover and to look for any evidence of primary coolant bypassing on a facility that could model the geometrical and thermal-hydraulic conditions of a Westinghouse Model F steam generator during SGTR/SORV faults. For this, the LOFTRAN code was used to define the thermal-hydraulic conditions expected during the fault and these were then used as the basis for a series of steady-state and transient tests.

For the basic transient it was assumed that an SGTR and a coincident SORV occurred at a time when off-site power was unavailable, but when auxiliary feedwater was maintained for 15000 seconds. The conditions predicted using the LOFTRAN code were used to define the full transient test, Test 12, and of the available parameters the primary pressure and primary temperature, T_{hot}, were selected as control parameters. In the actual test these parameters were followed accurately, as is shown in Figure 7-1, in spite of a plant trip which occurred partway through the test.

Within the overall transient three steady-state instances were selected at which the relative importance of moisture carryover and primary coolant bypassing were to be assessed. These were at 900, 4000 and 15000 seconds, as shown on Figure 7-1. At these instances the following characteristics were anticipated:

900 seconds: At this early stage in the transient the reactor scram will have occurred, but primary pressure will still remain high as no operator action will have been taken to reduce primary pressure. Under these conditions primary and secondary temperatures and pressures are such that the tube rupture flow will enter the secondary side at high velocity, but with little flashing. In the original test matrix, with T_{hot} at 560°F, only 0.83% of the primary coolant would flash, whereas in the modified tests, with T_{hot} at 580°F, flashing would be increased to 5.12%. These give voidage levels in the emerging jet of 0.14 and 0.50, respectively, for the break flow. Under

these conditions there was the possibility that primary coolant bypassing could occur and since steam velocities were low, 2% or 10% respectively, that the performance of the primary separator and dryer would be impaired.

4000 seconds: By this time the operators are assumed to have taken steps to reduce the primary coolant pressure and the faulted steam generator would be isolated. Following these actions the difference in temperature between the primary and secondary side can increase, which could promote flashing of the break flow and increase fission product release via primary coolant bypassing. In the original test matrix with T_{hot} at 427°F, 1.34% of the jet was expected to flash to give a voidage level of 0.53 in the emerging jet. In the revised test designed to promote flashing, these values become 470°F, 6.64% and 0.84, respectively.

15000 seconds: At later stages in the transient the tube rupture flow will have a low discharge velocity and only a small temperature difference will exist between primary and secondary fluids. Only low levels of flashing are expected, but voidage levels will remain significant due to the large specific volume of steam at these temperatures. Under these conditions mixing of the break flow and the bulk liquid would be expected and bypassing would be small. However, as the steam velocities will now be very low, the efficiencies of the separators and dryers may be further impaired. These conditions after 15000 seconds are similar to those which would be expected to exist from about 10000 seconds onwards and up to cold shutdown. As planned with T_{hot} at 320°F and a secondary pressure of 85 psia, only 0.47% of the break flow should flash and the voidage would be 0.58. In the test the actual values obtained were 324°F and 81 psia respectively, which gave increased flashing, 1.21%, and voidage, 0.79.

The thermal-hydraulic conditions for the original steady-state tests were confirmed using the NOTRUMP code. In the actual tests these conditions were maintained satisfactorily, as were those of the revised steady-state tests. The revised conditions specified for the 900 second steady-state time period were taken as the basis for the group of tests carried out over a range of low water levels. Although these test conditions lay outside the normal operating range for the MB-2 facility, in general the desired test conditions were maintained in each test. The only exceptions to this was the need to increase T_{hot} at very low water levels and the increased difficulty in maintaining the specified water levels.

In the two overfill tests, Tests 10 and 11, the test conditions selected were similar to those used in the SGTR/SORV tests and approximate the early stage in an SGTR transient following reactor scram (T_{hot} 580°F rather than 617°F), but with lower primary heat flux as under hot standby conditions. The limits for the operation of the safety relief valve were taken as 1200 psia and 1000 psia for opening and closing, respectively. The value of 1200 psia was taken as typical for the operation of the code safety relief valve with the lowest pressure setting. In carrying out these tests no difficulty was encountered in obtaining the initial thermal-hydraulic conditions, but overfilling the MB-2 model boiler proved more difficult than anticipated. In Test 10 this was in part due to the continued operation of the 2% SORV steam line in the initial stages of the test, but in both tests it was mainly due to the loss of water to the void space of the model boiler once the water level was sufficient to flood the dryer. Because of the latter effect, in both tests, auxiliary feedwater had to be supplied in addition to the SGTR break flow to raise level and pressure at a satisfactory rate.

As part of the test program, three moisture carryover tests were carried out to provide comparative data for the SGTR tests. Of these, the 8% moisture carryover test was carried out under conditions similar to those specified for the steady-state tests after 900 seconds and the test conditions were met satisfactorily. In the two 100% power tests most thermal-hydraulic parameters were maintained satisfactorily, but in both tests the feedwater temperature was low due to the loss of feedheater surface area. In addition, as the SORV condenser could not handle the full steam flow, the main steam line was used in both tests, with the 8% SORV steam line acting as a steam sampling line. While this could lead to errors in determining moisture carryover, the rapid increase in carryover seen in Test 7 when the dryers flooded and that seen in Test 13 when the water level was raised would suggest that gross errors were absent.

Throughout the test series the principal objective was to establish the level of moisture carryover and that of primary coolant bypassing. This was to be achieved by the use of two different chemical tracers, namely lithium hydroxide for the model boiler water and potassium hydroxide for the primary coolant. These particular tracers were selected because they could be detected and analyzed at low concentration, did not have high steam volatilities, were not prone to gross contamination and were not expected to cause unacceptable corrosion damage to the test facility. In each test moisture carryover from the bulk steam generator water was to be determined by measuring the lithium in the condensed SORV steam and in the model boiler water. During the SGTR phases of the tests the corresponding measurements for potassium would give the total carryover of primary coolant. This would in part be due to primary coolant that had mixed with the bulk model boiler water and was released by moisture carryover and, in part, would be due to that fraction of the emerging SGTR break flow which escapes directly in the steam, the process defined as primary coolant bypassing.

Because of the importance associated with the measurement of the tracers in the condensed SORV steam (SORV condensate) and in the model boiler water, additional, continuously flowing sample lines were installed for the Phase II test program and measures taken to ensure that the analytical results were of sufficient precision and were free from error. These are described fully in Sections 2-2-5 and 4.0. Due to the low levels of carryover observed and because model boiler samples were taken from a boiling water source, the principal analytical problems centered on the measurement of very low concentrations of tracer in the SORV condensate and on whether the samples taken from the model boiler were representative of the liquid phase alone.

For the SORV condensate samples an assessment of the data, given in Section 7-1, shows that the measured concentrations were correct and that they were not influenced by analytical bias, sample contamination or plateout. However, volatility data would indicate that, at the tracer levels generally used, the volatilities of both lithium hydroxide and potassium hydroxide at normal secondary pressures are comparable to the measured concentrations and that the observed very low carryover could be due to steam volatility rather than to droplet carryover. At lower pressures, as in Tests 3, 4, 5 and 14, the volatilities would be such that no contribution from volatility would be anticipated.

The interpretation of the data for the model boiler water sample lines was more difficult because of changes in conditions at the sample takeoff points at different water levels. At normal or high water an assessment using mass balances showed that the sample lines gave accurate results, but at lower level the measured concentrations were low due to the sampling of two-phase mixtures. Fortunately, it was possible to correct these concentrations using mass balance arguments, but at very low level the data indicated that hideout occurred and meaningful concentrations could not be derived.

Overall, the data show that the desired thermal-hydraulic conditions were achieved under all test conditions and that they accurately model those expected in a Model F steam generator. For each test the assessment of the chemical data show that the SORV condensate results can be expected to be correct and that suitable corrections can be derived for the model boiler water samples, so that the concentrations in the model boiler can be established. From these results we can be confident that the estimates of both carryover and primary coolant bypassing are free from major experimental inaccuracy.

543

7-5. REFERENCES

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TABLE 7-1

PREDICTED CONTRIBUTION OF VOLATILITY TO OBSERVED CARRYOVER

	LITHIUM HYDROXIDE			POTASSIUM HYDROXIDE		
SECONDARY PRESSURE (psia)	MODEL BOILER CONCENTRATION (ppm)	SORV CONDENSATE CONCENTRATION (ppb)	PARTITION COEFFICIENT K_{app}	MODEL BOILER CONCENTRATION (ppm)	SORV CONDENSATE CONCENTRATION (ppb)	PARTITION COEFFICIENT K_{app}
1000 - 1080	10	0.02	$1.6x10^{-6}$	100	0.01	$1.2x10^{-7}$
	20	0.05	$2.5x10^{-6}$	200	0.06	$3.1x10^{-7}$
	40	0.12	$3.0x10^{-6}$	300	0.18	$4.4x10^{-7}$
	60	0.27	$4.5x10^{-6}$	400	0.24	$5.9x10^{-7}$
	80	0.50	$6.3x10^{-6}$	600	0.53	$8.9x10^{-7}$
	100	0.80	$8.0x10^{-6}$	800	0.96	$1.2x10^{-6}$
	200	3.20	$1.6x10^{-5}$			
287 - 305	40	<< 0.01	$\simeq 1x10^{-8}$	20	<< 0.01	$< 1x10^{-9}$
	60			40		
	80			60		
				100		
				200		
				300		
85	40	<< 0.01	$<< 1x10^{-9}$	10	<< 0.01	$<< 1x10^{-9}$
				20		
				30		

The apparent partition coefficient, K_{app}, was estimated by extrapolation of the data of Stephan and Kuske[1] at 3118, 2900, 2320 and 1740 psia using the power law $K_{app} = (\frac{\rho_w}{\rho_s})^n$, where ρ_s and ρ_w are the densities of the steam and water phases in the model boiler.

TABLE 7-2

COMPARISON OF OBSERVED AND CALCULATED CONDUCTIVITIES

TEST REFERENCE NO.	S-1 SAMPLE				IKP-4 SAMPLE				PRIMARY SAMPLE		
	ANALYSIS		CONDUCTIVITY (µS/cm)		ANALYSIS		CONDUCTIVITY (µS/cm)		ANALYSIS	CONDUCTIVITY (µS/cm)	
	Li (ppm)	K (ppm)	OBSERVED	CALCULATED	Li (ppm)	K (ppm)	OBSERVED	CALCULATED	K (ppm)	OBSERVED	CALCULATED
T-1952	40	-	405	1371	40	-	401	1371	50	240	349
	34	236	945	2811	35	208	895	2650	-	-	-
T-1957	94	-	2802	3221	-	-	-	-	-	-	-
T-1958	50	-	1458	1714	66	-	1808	2262	53	207	370
	33	220	2402	2665	33	210	2454	2596	-	-	-
T-1966	50	-	860	1714	51	-	762	1748	-	-	-
T-1970	41.5	-	900	1422	42	-	865	1440	40	207	279
	42	92	1251	2082	41	81	1212	1970	-	-	-
T-1972	45	-	912	1542	45	-	892	1542	41	218	296
	37	30	879	1460	36	31	870	1450	-	-	-
T-1975 to	50	-	784	1714	50	-	779	1714	52	195	363
T-1979	5	130	490	1078	7	166	605	1386	-	-	-
T-1982	42	-	848	1440	42	-	862	1440	47	205	328
	40	88	1292	1984	40	88	1312	1964	-	-	-
T-1988 to	58	-	942	1986	65	-	1018	2228	46	172	314
T-1992	11	132	510	1266	15	166	680	1672	-	-	-
T-1998	10	-	337	343	9.5	-	351	325	16	81	116
	2	13	151	160	2	12	127	153	-	-	-
T-2001	11	-	345	377	10	-	318	343	8	68	56
	4	25	233	311	3	24	244	268	-	-	-
T-2003	11	-	366	377	11	-	381	377	8	76	56
	2	16	168	181	2	22	235	222	-	-	-
T-2050 to	8	-	268	274	8	-	268	274	53	295	370
T-2054	0.34	210	1473	1477	0.46	275	2068	1838	-	-	-
T-2061 to	58	-	1177	2021	51	-	1317	1748	53	335	370
T-2065	7	255	1287	2416	11	285	1705	3018	-	-	-

TABLE 7-2 (Continued)

COMPARISON OF OBSERVED AND CALCULATED CONDUCTIVITIES

TEST REFERENCE NO.	S-1 SAMPLE				IKP-4 SAMPLE				PRIMARY SAMPLE		
	ANALYSIS		CONDUCTIVITY	(µS/cm)	ANALYSIS		CONDUCTIVITY	(µS/cm)	ANALYSIS	CONDUCTIVITY	(µS/cm)
	Li (ppm)	K (ppm)	OBSERVED	CALCULATED	Li (ppm)	K (ppm)	OBSERVED	CALCULATED	K (ppm)	OBSERVED	CALCULATED
T-2067	37	-	1251	1267	36	-	1306	1234	50	201	349
	37	61	1484	1676	36	58	1545	1710	-	-	-
T-2068	36	-	804	881	-	-	-	-	-	-	-

Conductivities were calculated using the equivalent conductivities at 25°C. They are not corrected for concentration, which would reduce the values, typically by about 5%. The measured results were all temperature compensated to 25°C; calibration data indicate that the readings are about 2% low.

TABLE 7-3

MASSES OF LITHIUM AND POTASSIUM ADDED TO MB-2

		LITHIUM		POTASSIUM			
Test	Water Level (in.)	Mass LiOH Added (g)	Mass Lithium (g)	Mass SGTR Flow (lb)	Primary Concentration (ppm)(a)	Mass Potassium Added (g)	Total Mass Potassium (g)
1 (T-1952)	442	~ 10	2.898(b)	4176	52	98.705	-
2 (T-1958)	442	~ 60	17.388	4640	50	105.045	-
3 (T-1970)	443	84	24.343	2637	39	46.747	-
4 (T-1982)	446	~ 85	24.633	2456	46	51.353	-
5 (T-1972)	440	~ 80	23.184	1281	40	23.291	-
6 (T-1957)	447	~ 200	57.960	-	-	-	-
7 (T-1966)	442	~ 80	23.184	-	-	-	-
8 (T-1975)	446	~ 80	23.184	-	-	-	-
8 (T-1976)	62	-	-	404	53	9.733	-
8 (T-1977)	104	-	-	812	53	19.562	29.295
8 (T-1978)	165	-	-	809	53	19.490	48.784
8 (T-1979)	280	-	-	806	52	19.051	67.835
9 (T-1988)	442	~ 100	28.980	-	-	-	-
9 (T-1989)	64	-	-	846	44	16.920	-
9 (T-1990)	100	-	-	878	44	17.560	34.480
9 (T-1992)	165	-	-	872	43.5	17.242	51.722
9 (T-1991)	285	-	-	868	43	16.965	68.687
10 (T-1998)	445	~ 18	5.216	4699	14.5	30.971	-
11 (T-2003)	483	~ 18	5.216	5528	8.5	21.358	-
12 (T-2001)	443	~ 18	5.216	6286	8	22.858	-
13 (T-2069)	442	~ 50	14.490	-	-	-	-
14 (T-2067)	447	~ 65	18.84	1305	50	29.659	-
14 (T-2067)	102	-	-	1305	50	29.659	-
15 (T-2050)	439	~ 20	5.796	-	-	-	-
15 (T-2051)	60	-	-	935	55	23.375	-
15 (T-2052)	100	-	-	960	55	24.000	47.375
15 (T-2053)	160	-	-	974	55	24.350	71.725
15 (T-2054)	285	-	-	975	55	24.375	96.100
16 (T-2061)	443	~ 100	28.980	-	-	-	-
16 (T-2062)	60	-	-	1002	57.5	26.188	-
16 (T-2063)	105	-	-	1051	59	28.186	54.374
16 (T-2064)	155	-	-	1042	59	27.945	82.319
16 (T-2065)	285	-	-	1042	60	28.418	110.738

NOTES:

(a) Average value for period of SGTR injection
(b) Total Mass = 18.837g (including preexisting dose)

548

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TABLE 7-4

ESTIMATES OF MB-2 LIQUID MASS AT NORMAL OR HIGH WATER LEVEL

		Estimate From Lithium Dose				Estimate From Potassium Injected			
Test	Level (in.)	Lithium Added (g)[(a)]	SORV + Sample Losses (g(Li))	Measured Concentration (ppm Li)	Calculated Liquid Mass MB-2 (lb)[(b)]	K Injected (g)	SORV + Sample Losses (g(K))	Measured Concentration (ppm K)	Calculated Liquid Mass MB-2 (lb)[(b)]
7 (T-1966) [(c)]	442	23.18	-	ΔLi = 60[(d)]	850	-	-	-	-
13 (T-2068) [(c,e)]	442	14.49	-	ΔLi = 38[(d)]	839	-	-	-	-
1 (T-1952)	442	2.90	-	ΔLi = 6[(f)]	1063	-	-	-	-
	470	18.84	1.10	34	1147	98.71	3.25	236	890
2 (T-1958)	442	17.39	1.34	33	1070	105.45	3.70	215	1041
6 (T-1957)	447	57.96	-	130	981	-	-	-	-
10 (T-1998)	445	5.22	-	9.5	1208	-	-	-	-
	~ 525	5.22	0.17	2	5548[(g)]	30.97	0.25	13	5199[(g)]
11 (T-2003)	483	5.22	-	11	1040	-	-	-	-
	~ 525	5.22	0.19	2	5533[(h)]	15.97	0.19	9	3875[(h)]
12 (T-2001)	443	5.22	-	10.5	1093	-	-	-	-
	~ 525	5.22	0.32	4	2692	22.86	1.00	24.4	1971
8 (T-1975)	446	23.18	-	50	1020	-	-	-	-
9 (T-1988)	442	28.98	-	58/65	981/1089	-	-	-	-
15 (T-2050) [(e)]	439	5.80	-	8	1594	-	-	-	-
16 (T-2061) [(e)]	443	28.98	-	51/59	934/1081	-	-	-	-
3 (T-1970)	443	24.34	-	41	1306	-	-	-	-
	457	24.34	0.98	41	1254	46.75	0.98	81	1243
4 (T-1982)	446	24.63	-	42	1290	-	-	-	-
	450	24.63	1.10	41	1263	51.35	1.09	85	1301
14 (T-2067) [(e)]	447	18.84	-	36	1151	-	-	-	-
	447	18.84	0.52	36	1120	29.66	0.33	56	1152
5 (T-1972)	440	23.18	-	45	1133	-	-	-	-
	~ 500	23.18	1.19	36.5	1325	23.29	0.48	30.5	1645

Notes:

(a) Dose in g Lithium = 0.2888 (LiOH dose)

(b) Liquid mass $= \dfrac{\text{Mass Li or K (g)} \times 1000 \times 2.2}{\text{Li or K Concentration (ppm)}}$ lb

(c) 100% power
(d) Estimated maximum from S-1 conductivity trace
(e) Secondary dryers bypassed
(f) Increase from pre-dose level of 33 ppm Li
(g) Final mass = 1208 + 4699 (SGTR) + auxiliary feedwater = > 5907 lb
(h) Final mass to start of boildown = 1040 + 4134 (SGTR) + auxiliary feedwater = > 5174 lb

TABLE 7-5

CALCULATED CONCENTRATIONS FOR TEST 2 (T-1958)

Run Time (min)	Water Level (ins)	Liquid Mass (lb)(a)	Sample Line	Calculated Mass in MB-2 (b)		Measured Concentrations (c)		Calculated Concentrations (d)		Ratio $\frac{Li}{K}$	
				Lithium (g)	Potassium (g)	Lithium (ppm)	Potassium (ppm)	Lithium (ppm)	Potassium (ppm)	Concentration Ratio	Mass Ratio
0	240	470	S-1	17.39	0	50	1.5	81	0	33.3	∞
0	240	470	IKP-4	17.39	0	66	4	81	0	16.5	∞
99	250	485	S-1	16.62	53.10	49	155	75	241	0.32	0.31
99	250	485	IKP-4	16.62	53.10	64	200	75	241	0.32	0.31
110	190	375	S-1	16.55	61.43	47	190	97	360	0.25	0.27
110	190	375	IKP-4	16.55	61.43	80	330	97	360	0.24	0.27
140	205	400	S-1	16.32	83.81	53	275	90	461	0.19	0.19
140	205	400	IKP-4	16.32	83.81	67	350	90	461	0.19	0.19

Notes:

(a) Estimated from Figure 6-1, using the total liquid mass and the corrected water level WL9321.

(b) Total mass added taken from Table 7-3 assuming a linear rate of input for the SGTR. Both masses corrected for losses via the SORV steam and model boiler sample lines.

(c) Corrected for sample line delays.

(d) Calculated using total liquid mass, assuming an insignificant dilution in the downcomers by the auxiliary feed water, and the calculated mass of lithium or potassium.

(f) Estimated scaling factors, S-1: 240-250 in., 1.53-1.62; 190-205 in., 1.68-2.06
IKP-4: 240-250 in., 1.17-1.22; 190-205 in., 1.08-1.33

TABLE 7-6

CALCULATED CONCENTRATIONS AND LITHIUM MASSES FOR LOW LEVEL TESTS WITH RECIRCULATION (a)

Test	Run Time (min)	Water Level (in.)	Liquid Mass (lb)	Sample Line	Calculated Mass in MB-2		Calculated Mass of Lithium At End of Blowdown (g)	Measured Concentrations		Calculated Concentrations	
					Lithium (g)	Potassium (g)		Lithium (ppm)	Potassium (ppm)	Lithium (ppm)	Potassium (ppm)
8 (T-1978) (T-1979)	460	280	540	IKP-4	2.71	64.22	3.11	7	166	11	262
	460	280	540	S-1	2.47	64.22	2.87	5	130	10	262
	435	280	540	IKP-4	2.66	64.67	3.04	7	170	11	263
	435	280	540	S-1	2.49	64.67	2.89	5	130	10	263
	400	280	540	IKP-4	2.69	46.18	3.05	7	120	11	188
	400	280	540	S-1	2.72	46.18	3.07	5	85	11	188
	355	165	325	IKP-4	2.81	46.85	3.13	12	200	19	317
	355	165	325	S-1	2.73	46.85	3.05	7	120	18	317
	325	165	325	IKP-4	2.66	27.88	2.93	10	105	18	189
	325	165	325	S-1	2.50	27.88	2.78	7	78	17	189
9 (T-1981) (T-1982)	440	285	550	IKP-4	5.34	59.14	6.15	15	166	21	237
	440	285	550	S-1	4.93	59.14	5.97	11	132	20	237
	420	285	550	IKP-4	5.42	59.99	6.38	15	166	22	240
	420	285	550	S-1	4.92	59.99	5.89	11	134	20	240
	380	285	550	IKP-4	5.34	44.15	6.15	15	124	21	177
	380	285	550	S-1	4.96	44.15	5.77	11	98	20	177
	340	165	325	IKP-4	5.94	45.61	6.58	25	192	40	309
	340	165	325	S-1	5.26	45.61	5.90	15	130	36	309
	300	165	325	IKP-4	6.14	29.75	6.57	26	126	42	201
	300	165	325	S-1	5.58	29.75	6.00	15	80	38	201

Notes:

(a) See Notes for Table 7-5, with the exception that the concentrations and masses are calculated from the data for potassium only.
(b) Secondary dryers bypassed.
(c) Scaling factors, S-1: -~ 285 in., ~ 2.0, (T-1979); ~ 1.7, (T-1981); ~ 1.7, (T-2054) and ~ 1.5 (T-2067)
~ 160 in., ~ 2.2, (T-1978); ~ 2.1, (T-1982); ~ 2.5, (T-2053) and ~ 2.3, (T-2064)
IKP-4: -~ 285 in., ~ 1.5, (T-1979); ~ 1.35, (T-1981); 1.2, (T-2054); and ~ 1.35, (T-2067)
~ 160 in., ~ 1.5, (T-1978); ~ 1.4, (T-1982); ~ 1.3, (T-2053) and ~ 1.5, (T-2064)

TABLE 7-6 (Cont.)

CALCULATED CONCENTRATIONS AND LITHIUM MASSES FOR LOW LEVEL TESTS WITH RECIRCULATION (a)

Test	Run Time (min)	Water Level (in.)	Liquid Mass (lb)	Sample Line	Calculated Mass in MB-2		Calculatem Mass of Lithium At End of Blowdown (g)	Measured Concentrations		Calculated Concentrations	
					Lithium (g)	Potassium (g)		Lithium (ppm)	Potassium (ppm)	Lithium (ppm)	Potassium (ppm)
	490	285	550	IKP-4	0.14	84.07	0.21	0.47	275	0.57	336
	490	285	550	S-1	0.14	84.07	0.21	0.35	210	0.56	336
	450	285	550	IKP-4	0.14	61.21	0.20	0.46	200	0.56	245
	450	285	550	S-1	0.14	61.21	0.20	0.33	140	0.58	245
	410	160	320	IKP-4	0.10	62.71	0.16	0.52	325	0.69	431
15 (b) (T-2053) (T-2054)	410	160	320	S-1	0.09	62.71	0.15	0.26	175	0.64	431
	390	160	320	IKP-4	0.12	63.70	0.17	0.66	360	0.80	438
	390	160	320	S-1	0.12	63.70	0.18	0.35	180	0.85	438
	365	160	320	IKP-4	0.13	40.43	0.18	0.64	200	0.89	278
	365	160	320	S-1	0.12	40.43	0.17	0.32	180	0.82	278
	445	285	550	IKP-4	3.75	97.18	4.49	11	285	15	389
	445	285	550	S-1	2.67	97.18	3.40	7	255	11	389
	395	285	550	IKP-4	3.85	71.67	4.45	11	205	15	287
	395	285	550	S-1	2.57	71.67	3.18	7	195	10	287
	370	155	310	IKP-4	4.06	73.25	4.58	18	325	29	520
16 (b) (T-2064) (T-2065)	370	155	310	S-1	2.60	73.25	3.13	8	225	18	520
	360	155	310	IKP-4	4.03	73.85	4.52	18	330	28	508
	360	155	310	S-1	2.56	73.85	3.05	9	260	18	508
	320	155	310	IKP-4	3.05	47.66	3.44	16	250	22	338
	320	155	310	S-1	2.80	47.66	3.19	8	136	20	338

Notes:

(a) See Notes for Table 7-5, with the exception that the concentrations and masses are calculated from the data for potassium only.
(b) Secondary dryers bypassed.
(c) Scaling factors, S-1: -~ 285 in., ~ 2.0, (T-1979); ~ 1.7, (T-1991); ~ 1.7, (T-2054) and ~ 1.5 (T-2067)
~ 160 in., ~ 2.2, (T-1978); ~ 2.1, (T-1992); ~ 2.5, (T-2053) and ~ 2.3, (T-2064)
IKP-4: -~ 285 in., ~ 1.5, (T-1979); ~ 1.35, (T-1991); 1.2, (T-2054); and ~ 1.35, (T-2067)
~ 160 in., ~ 1.5, (T-1978); ~ 1.4, (T-1992); ~ 1.3, (T-2053) and ~ 1.5, (T-2064)

TABLE 7-7

CALCULATED AND MEASURED RATIOS OF TRACER CHEMICALS FOR LOW LEVEL TESTS WITHOUT RECIRCULATION

Test	Run Time (min)	Water Level (in.)	Liquid Mass (lb)	Sample Line	Measured Concentrations Lithium (ppm)	Measured Concentrations Potassium (ppm)	Calculated Mass (b) Lithium (g)	Calculated Mass (b) Potassium (g)	Ratio Li/K Concentration Ratio	Ratio Li/K Mass Ratio
	275	104	150	IKP-4	5	176	2.83	28.87	0.028	0.098
8	245	104	150	IKP-4	0.58	1	2.89	9.60	0.580	0.301
(T-1976)	205	56	65	IKP-4	1	8	2.93	9.71	0.125	0.302
(T-1977)	184	62	71	IKP-4	0.26	0.01	3.02	0	26	∞
	250	86	115	IKP-4	1	280	5.71	31.51	0.0036	0.181
9	215	102	147	IKP-4	1.5	23	5.73	14.93	0.065	0.384
(T-1989)	170	66	72	IKP-4	1	390	5.81	16.64	0.0026	0.349
(T-1990)	140	64	72	IKP-4	0.4	2	5.83	0	0.2	∞
	300	95	140	IKP-4	2	365	0.162	43.40	0.0055	0.0037
15 (d)	290	100	145	IKP-4	2	400	0.164	43.98	0.0050	0.0037
(T-2051)	280	100	145	IKP-4	0.27	16	0.175	21.69	0.017	0.0081
(T-2052)	190	60	70	IKP-4	0.42	6	0.184	23.19	0.070	0.0079
	180	60	70	IKP-4	0.32	12	0.187	23.24	0.038	0.0080
	150	60	70	IKP-4	0.1	0.0054	0.201	0	18.5	∞
	270	105	150	IKP-4	6	230	3.05	50.56	0.026	0.060
16 (d)	240	105	150	IKP-4	8	75	3.09	23.59	0.107	0.131
(T-2062)	165	60	70	IKP-4	6	380	3.21	25.73	0.016	0.125
(T-2063)	135	60	70	IKP-4	0.13	0.28	3.23	0	0.46	∞

Notes:

(a) Liquid mass in bundle only, taken from Figure 6-1. Mass in downcomer assumed to be undosed auxiliary feed water.

(b) Calculated mass of lithium at end of blowdown, estimated as, 3.05g (T-1975); 5.88g; (T-1988); 0.205g, (T-2050) and 3.29g, (T-2061). Lithium mass at any individual run time estimated from these masses, minus the SORV steam and sample line losses. Potassium mass calculated as in Table 7-5.

(c) Calculated lithium concentrations at the end of blowdown estimated as, 118 ppm, (T-1975); 227 ppm, (T-1988); 9.0 ppm, (T-2050) and 111 ppm, (T-2061)

(d) Secondary dryers bypassed

TABLE 7-8

CALCULATED CONCENTRATIONS FOR TEST 14 (T-2067)

Run Time (min)	Water Level (in.)	Liquid Mass (lb)	Calculated Mass in MB-2 (b)		Measured Concentrations		Calculated Concentrations		Ratio Li/K	
			Lithium (g)	Potassium (g)	Lithium (ppm)	Potassium (ppm)	Lithium (ppm)	Potassium (ppm)	Concentration Ratio	Mass Ratio
0	440	~ 1150	18.84	0	35	0.08	36	0	450	∞
80	440	~ 1150	18.32	29.33	36	58	35	56	0.62	0.62
105	102.5	205.6	5.46	8.74	45	72	58	94	0.63	0.62
120	102.5	205.6	5.34	9.11	44	75	57	97	0.59	0.59
190	102.5	205.6	5.22	37.65	43	310	56	403	0.14	0.14

Notes:

(a) Mass at 440 in. taken from Table 7-4. Mass at 102.5 in. estimated from density distribution and using only the mass in the tube bundle. AT 102.5 in. the downcomers are assumed to be full of undosed auxiliary feed water (downcomer mass = 55.9 lb.)

(b) Mass at 440 in. calculated directly from lithium and potassium added in the first stage of the test. Masses at 102.5 in. calculated from the mass of potassium added during the second SGTR injection (28.54g after correcting for sample losses) and equating this with a measured increase of 235 ppm potassium.

TABLE 7-9

STEADY-STATE CARRYOVER AT NORMAL OR HIGH WATER LEVEL

		Lithium			Potassium		
Test	Level (in.)	SORV Condensate (ppb)	MB-2 (ppm)	Carryover (%)(a)	SORV Condensate (ppb)	MB-2 (ppm)	Carryover (%) (a)
7(T-1966) (b)	442 to 485	0.8 to 0.6	50 to 20	0.0016 to 0.001	-	-	-
13(T-2069) (b,c)	442	0.6 to 0.4	26 to 23	0.0023 to 0.0017	-	-	-
13(T-2069) (b,c)	465	2.2	18	0.012	-	-	-
1 (T-1952)	442 to 470	~ 0.2	40	~ 0.00050	~ 1.0	240	~ 0.00042
2 (T-1958)	442	~ 0	33	< 0.00061 (d)	~ 0	215	< 0.000093 (d)
6 (T-1957)	442 to 485	0.9 to 0.5	94 to 82	0.00096 to 0.00061	-	-	-
10 (T-1986)	445 to 525	0 to 0.3	10	< 0.002 (d) to 0.003	0.2 to 0.6	16	0.0013 to 0.0038
11 (T-2003)	483	~ 0	11	< 0.0018 (d)	-	-	-
12 (T-2001)	443 (e)	0.2 to 0.3	11	0.0018 to 0.0027	0.4 to 0.8	0 to 10	0.004 to 0.008
12 (T-2001)	to	~ 0	5 to 7	< 0.0029 (d)	0 to 0.8	20 to 30	< 0.0067 (d) to 0.0027
12 (T-2001)	525 (f)	0.2 to 0.3	4 to 5	0.004 to 0.008	0 to 0.6	30 to 33	< 0.00061 (d) to 0.0018
8 (T-1975)	446 to 130	0 to 0.2	50	≤ 0.00040	-	-	-
9 (T-1988)	442 to 130	0 to 0.3	65	< 0.00031 (d) to 0.00046	-	-	-
15 (T-2060) (c)	439 to 130	~ 0	8	< 0.0025 (d)	-	-	-
16 (T-2061) (c)	443 to 130	0.2 to 0.6	59	0.00034 to 0.0010	-	-	-
3 (T-1970)	443 to 457	~ 0	41	< 0.00049 (d)	0 to 0.2	81	≤ 0.00025
4 (T-1982)	446 to 450	~ 0	42	< 0.00050 (d)	~ 0.2	88	0.00023
14 (T-2067) (c)	447 to 450	~ 0 (g)	36	< 0.00056 (d)	-	-	-
14 (T-2067) (c)	447 to 450	~ 0.2 (h)	36	~ 0.00056	0.3 to 0.4	58	0.00052 to 0.00069
5 (T-1972)	440 to 500	~ 0	45	< 0.00044 (d)	~ 0.5	31	0.0016

Notes:

(a) Precisions may be calculated from the data given in Table 4-1 and from the Tables given in Section 5.0. Typically, in tests where the concentration in MB-2 was ~ 10 ppm, the precision was ± 0.002%, at ~ 50 ppm, ± 0.0004% and at ~ 200 ppm, ± 0.0001%
(b) 100% power
(c) Secondary dryers bypassed
(d) Based on the limit of detection of 0.2 ppb
(e) Before 10% SORV flow
(f) At end of test
(g) Before SGTR
(h) During SGTR

TABLE 7-10

UPPER LIMITS FOR STEADY-STATE PRIMARY COOLANT BYPASSING AT NORMAL OR HIGH WATER LEVEL

		Mass Output		Mass Input		
Test (a)	Level (in.)	SORV Concentration (ppb)	SORV Flow Rate (kg/min)	Primary Concentration (ppm)	SGTR Flow Rate (kg/min)	Bypass (%) (a)
1 (T-1952)	442 to 470	~ 1.0	12.27	50 to 54	16.09	0.0014 to 0.0015
12 (T-2001)	443 to 525	0 to 0.4	28 to 4.9	8	21 to 6.3	0.0032 to 0.0063 (b) < 0.0038 to 0.017 (c)
3 (T-1970)	443 to 457	~ 0.2	12.27	37 to 41	10.36	0.00058 to 0.00064
4 (T-1982)	446 to 450	~ 0.2	16.36	47 to 43	9.55	0.00073 to 0.00080
14 (T-2067) (d)	447 to 450	0.3 to 0.4	14.73	50	10.09	0.00088 to 0.0012
5 (T-1972)	440 to 500	~ 0.5	2.73	40 to 41	4.91	0.00068 to 0.00070

Notes:

(a) For precisions see notes to Table 7-9
(b) Before 10% SORV flow
(c) At end of test
(d) Secondary dryers bypassed

TABLE 7-11

TRANSIENT RELEASES AT NORMAL OR HIGH WATER LEVEL

		Lithium Release			Potassium Release			
Test	Transient	SORV Mass Released (mg)	Mass In MS-2 (g)	Carryover (%)	SORV Mass Released (mg)	Mass in MS-2 or Mass Injected (g)	Carryover (%)	Bypass (Upper Limit) (%) (a)
1 (T-1952)	At start SGTR?	0	-	0	0.276	0.335$^{(b)}$	-	0.082
4 (T-1982)	At start SGTR?	0.067	24.19	0.00028	0.049	0-187$^{(b)}$	-	0.026
14 (T-2067) (c)	At start SGTR	0.057	23.02	0.00025	0.295	0.280$^{(b)}$	-	0.105
12 (T-2001)	Pressure relief 42.5 min.	0.044	5.13	0.00086	0.327 0.327	1.680 0.160$^{(d)}$	0.019 -	- 0.20
12 (T-2001)	2% to 10% SORV	0	-	0	1.061 1.061	4.080 0.204$^{(d)}$	0.026 -	- 0.52
11 (T-2003) (e)	Cycle 1	0.465	5.125	0.0091	1.727 1.727	3.19 0.340$^{(d)}$	0.054 -	- 0.51
	Cycle 2	2.546	5.096	0.050	1.597 1.597	7.10 0.319$^{(e)}$	0.022 -	- 0.50
	Cycle 3	(f)	-	-	(f)	-	-	-
	Cycle 4	(f)	-	-	(f)	-	-	-
	Cycle 5	3.061	3.63	0.084	5.408	8.18	0.066	-
	Cycle 6	7.047	1.82	0.39	30.872	8.18	0.38	-

(a) Equivalent times for 100% bypass, Test 1, 0.021 sec.; Test 4, 0.007 sec.; Test 14, 0.026 sec.; Test 12, 0.16 and 0.42 sec.; Test 11, 0.38 and 0.40 sec.
(b) Over 25 sec. Rates - Test 1, 50 ppm @ 16.09 kg/min; Test 4, 47 ppm @ 9.55 kg/min; Test 14, 50 ppm @ 10.09 kg/min
(c) Secondary dryers bypassed
(d) Over 80 sec. Rates - Test 12, 8 ppm @ 15 or 19.09 kg/min., Test 11 (Cycle 1), 7 ppm @ 15 kg/min
(e) Over 75 seconds. Rate: 17 ppm @ 15 kg/min
(f) No loss to void assumed in Cycles 1 and 2. Mass of 2000 lb assumed in Cycles 5 and 6. Insufficient data for Cycles 3 and 4.

537

TABLE 7-12

COMPARISON OF TRACER CONCENTRATIONS IN SORV CONDENSATE AND IN MODEL BOILER WATER DURING THE PRESSURE RELIEF CYCLES OF TEST 11 (T-2003)

Pressure Relief Cycle	SORV Condensate at 30 Seconds		Model Boiler Water (S-1) (a)		Ratio SORV/S-1	
	Lithium (ppb)	Potassium (ppb)	Lithium (ppm)	Potassium (ppm)	Lithium	Potassium
1	2.6	12.2	10.5	1	0.02	1.20
2	16	7.6	10	5	0.16	0.15
3	13.6	12.4	8.5	7	0.16	0.18
4	14.4	16.6	6	8	0.24	0.21
5	14.4	20	4	9	0.36	0.22
6	15	50	4	9	0.50	0.56

(a) Inerterpolated from plotted data

TABLE 7-13

STEADY-STATE CARRYOVER AT LOW WATER LEVEL

Test	Phase	Level (in.)	Lithium			Potassium		
			SORV Condensate (ppb)	MB-2 (ppm)	Carryover (%)(a)	SORV Condensate (ppb)	MB-2 (ppm)	Carryover (%) (a)
8 (T-1975)	Blowdown	446 to 130	0 to 0.2	50	≤ 0.00040	-	-	-
9 (T-1988)		442 to 130	0 to 0.3	65	< 0.00031 to 0.00046 (c)	-	-	-
15 (T-2050) (b)		439 to 130	~ 0	8	< 0.0025	-	-	-
16 (T-2061) (b)		443 to 130	0.2 to 0.6	59	0.00034 to 0.0010	-	-	-
10 (T-1998)	Boildown	~ 525 to 20	~ 0	2	< 0.010 (c)	~ 0	12	< 0.0017 (c)
11 (T-2003)	Boildown + SGTR	~ 525 to 50	~ 0	2	< 0.010 (c)	~ 0	22	< 0.00091 (c)
2 (T-1958)	SGTR	240 to 250	~ 0	75 to 81	< 0.00027 (c)	~ 0	241	< 0.000083 (c)
2 (T-1958)	SGTR	190 to 205	~ 0.5	90 to 97	0.00052 to 0.00056	0.3 to 0.7	360 to 461	0.000065 to 0.000083
11 (T-208)	Post-Boildown	~ 40	~ 1.4	~ 100	~ 0.0014	~ 30	~ 1100	~ 0.0027
8 (T-1975)	Post-Blowdown	54 to 62	4 to 6	95 to 118	0.0034 to 0.0063	-	-	-
9 (T-1988)		54 to 62	10 to 14	182 to 227	0.0044 to 0.0077	-	-	-
15 (T-2050) (b)		48 to 62	0.4 to 1.0	6.3 to 9.0	0.0044 to 0.016	-	-	-
16 (T-2061) (b)		57 to 62	~ 5.8	102 to 111	0.0052 to 0.0057	-	-	-
8 (T-1976)	SGTR Post-SGTR	~ 62	< 11	99	< 0.011	~ 60	329	~ 0.018
9 (T-1989)		~ 64	3 to 9	174	0.0017 to 0.0052	~ 50	508	~ 0.0088
15 (T-2051) (b)		~ 60	< 1.6	5.8	< 0.028	~ 120	729	~ 0.016
16 (T-2062) (b)		~ 60	~ 2.4	101	~ 0.0024	~ 50	809	~ 0.0062
8 (T-1977)	Pre-SGTR	~ 104	< 7	42	< 0.017	< 20	140	< 0.014
9 (T-1990)		~ 100	< 2.9	85	< 0.0034	< 150	211	< 0.071
15 (T-2052) (b)		~ 100	1.8 to 2.5	2.7	0.067 to 0.093	370 to 600	329	0.11 to 0.18
16 (T-2063) (b)		~ 105	< 12.8	45	< 0.028	< 220	346	< 0.064
8 (T-1977)	SGTR + Post-SGTR	~ 104	< 6.9	42	< 0.016	< 150	423	< 0.035
9 (T-1990)		~ 100	< 1.5	108	< 0.0014.	< 110	592	< 0.019
15 (T-2052) (b)		~ 100	~ 0.6	2.5	~ 0.024	< 120	682	< 0.018
16 (T-2063) (b)		~ 105	< 7.6	45	< 0.017	550 to 650	742	0.074 to 0.088
14 (T-2067) (b)	SGTR	~ 102.5	0 to 0.2	56 to 58	≤ 0.00036	0 to 0.8	94 to 403	< 0.00005 to 0.00085

(a) For precisions at normal water level see Table 7.9. Where estimates based on calculated mass are used, the precision has not been assessed, but is probably to within a few percent.

(b) Secondary dryers bypassed

(c) Based on the level of detection of 0.2 ppb.

(d) The quoted results for Tests 8, 9, 15 and 16 during SGTRs at 60 and 100 in. should be regarded with caution, as neither the true SORV condensate nor the MB-2 concentrations can strictly be estimated. The concentrations calculated in MB-2 assume no hideout and use the masses given in Table 7-7.

TABLE 7-14

UPPER LIMITS FOR STEADY-STATE PRIMARY COOLANT BYPASSING AT LOW WATER LEVEL

Test	Level (in.)	Mass Output SORV Concentration (ppb)	SORV Flow Rate (kg/min)	Mass Input Primary Concentration (ppm)	SGTR Flow Rate (kg/min)	Bypass (a) (%)
8 (T-1976)	~ 62	~ 60	50.45	53	13.36	0.43
9 (T-1989)	~ 64	~ 50	51.82	44	13.91	0.42
15 (T-2051) (b)	~ 60	~ 120	51.82	55	14.59	0.77
16 (T-2062) (b)	~ 60	~ 50	51.82	59	14.59	0.30
8 (T-1977)	~ 104	~ 150	50.45	53	13.64	1.05
9 (T-1990)	~ 100	~ 110	50.45	44	16.23	0.78
15 (T-2052) (b)	~ 100	~ 120	51.82	55	16.09	0.70
16 (2063) (b)	~ 105	~ 650	50.45	59	16.09	3.45
14 (T-2067) (b)	~ 102.5	0 to 0.2	14.45 to 15.55	52	9.54 to 10.36	≤ 0.00054 (c)
2 (T-1958)	240 to 250	~ 0	40.91	50 to 53	15.82	< 0.0010 (c)
2 (T-1958)	190 to 205	0.3 to 0.7	40.91	47 to 50	15.82	0.0017 to 0.0036

(a) For precisions see notes to Table 7-9.

(b) Secondary dryers bypassed

(c) Based on the limit of detection of 0.2 ppb

TABLE 7-15

TRANSIENT RELEASES AT VERY LOW WATER LEVEL

Test	Transient	Level (in.)	Lithium Release			Potassium Release			Bypass (Upper Limit) (%) (b)
			SORV (a) Mass Released (mg)	Mass in MB-2 (g)	Carryover (%) (b)	SORV (a) Mass Released (mg)	Mass in MB-2 or Mass Injected (g) (c)	Carryover (%)	
8 (T-1975)		~ 130	20.6	.05	0.68	-	-	-	-
9 (T-1988)	Blowdown	~ 130	23.5	5.88	0.40	-	-	-	-
15 (T-2050) (d)		~ 130	1.37	0.205	0.67	-	-	-	-
16 (T-2061) (d)		130 to 150	41.5	3.29	1.26	-	-	-	-
8 (T-1976)		62	85.1	3.02	2.82	0	-	0	0
9 (T-1989	Start	64	0	5.83	0	0	-	0	0
15 (T-2051) (d)	SGTR	60	16.4	0.201	8.16	0	-	0	0
16 (T-2062) (d)		60	6.7	3.23	0.21	4.25	0	0	-
			-	-	-	4.25	0.369	-	1.15 (e)
8 (T-1976)			48.5	2.93	1.66	117	9.71	1.20	-
9 (T-1989)	Level	60 to 100	84.6	5.81	1.46	1122	16.64	6.74	-
15 (T-2051) (d)	Change		5.57	0.180	3.09	1302	23.13	5.63	-
16 (T-2062) (d)			82.8	3.21	2.58	1355	25.45	5.26	-
8 (T-1977)		104	30.9	2.89	1.07	139	9.60	1.45	-
			-	-	-	139	0.337	-	(41.2)
9 (T-1990)	Start	102	0	5.73	0	204	14.93	1.36	-
	SGTR		-	-	-	204	0.300	-	(68.0)
15 (T-2052) (d)		100	5.48	0.175	3.13	432	21.69	1.99	-
			-	-	-	432	0.363	-	(119)
16 (T-2063) (d)		105	31.2	3.09	1.01	1026	23.59	4.34	-
			-	-	-	1026	0.402	-	(255)
8 (T-1977)	Level		17.0	2.83	0.60	454	28.87	1.57	-
9 (T-1990)	Change	100 to 160	74.6	5.71	1.31	901	31.51	2.86	-
15 (T-2052) (d)			2.19	0.159	1.38	503	42.73	1.18	-
16 (T-2063) (d)			96.7	3.04	3.18	819	49.57	1.65	-
14 (T-2067) (d)	Start SGTR	102	0.156	5.34	0.0029	6.57	9.11	0.072	-
			-	-	-	6.57	0.204	-	3.22 (e)
11 (T-2003)	2% to 8% SORV + SGTR	23	14.9	1.82	0.82	125	8.18	1.53	-
			-	-	-	125	0.186	-	67.2 (e)

(a) Mass released during SGTRs calculated assuming an instantaneous release at the start of the SGTR followed by an exponential decay. During level changes a linear increase in concentration was assumed (except where there were sufficient data), followed by an exponential decay

(b) For precisions see notes in Tables 7-9 and 7-13

(c) Mass injected at the start of the SGTRs calculated over a 25 second period, that in Test 11 over a 72 second period.

(d) Secondary dryers bypassed

(e) Equivalent times for 100% bypass, Test 16, 0.29 sec; Test 14, 0.81 sec.; Test 11, 48 sec.

561

TABLE 7-16

TRANSIENT RELEASES AT INTERMEDIATE WATER LEVEL

Test	Transient	Level (in.)	Lithium Release: SORV (a) Mass Released (mg)	Lithium Release: Mass in MB-2 (g)	Lithium Release: Carryover (%) (b)	Potassium Release: SORV (a) Mass Released (mg)	Potassium Release: Mass in MB-2 or Mass Injected (g) (c)	Potassium Release: Carryover (%) (b)	Bypass (Upper Limit) (%) (b)
8 (T-1977)		165	0	2.65	0	7.77	27.81	0.028	-
		165	-	-	-	7.77	0.330	-	2.35
9 (T-1992)		165	0	5.52	0	0	29.46	0	-
	Start SGTR	165	-	-	-	0	0.300	-	0
5 (T-2053) (d)		160	0.58	0.129	0.45	15.6	40.43	0.039	-
		160	-	-	-	15.6	0.350	-	4.46
16 (T-2064) (d)		155	0	2.79	0	220	47.48	0.46	-
		155	-	-	-	220	0.400	-	55
8 (T-1977)		160	0	2.73	0	3.64	46.85	0.0078	-
9 (T-1992)	Level	To	0	5.26	0	0	45.61	0	-
15 (T-2053) (d)	Change	280	20.5	0.100	0	53.3	62.43	0.085	-
16 (T-2064) (d)			~ 10	2.60	0.38	350	73.25	0.48	-
8 (T-1978)		280	0	2.69	0	7.19	46.04	0.016	-
		280	-	-	-	7.19	0.340	-	2.11
9 (T-1991)	Start	285	0	5.30	0	0	43.83	0	-
	SGTR	285	-	-	-	0	0.300	-	0
15 (T-2054) (d)		285	0	0.141	0	18.2	61.21	0.030	-
		285	-	-	-	18.2	0.350	-	5.20
16 (T-2065) (d)		285	~ 10	2.56	0.39	50	71.40	0.070	-
		285	-	-	-	50	0.385	-	1.27
	Start SGTR +	250 to 200	0.51	17.13	0.003	0.35	0	-	-
2 (T-1958)	Boildown		-	-	-	0.35	0.356	-	0.088 (e)
	Boildown	250 to 190	0.83	16.55	0.005	1.96	87.89	0.0022	-
	+ SGTR		-	-	-	1.96	1.14	-	0.17

(a) Mass released generally estimated directly from the plotted results after correcting for the background concentrations arising the 100 to 160 in. level increase.

(b) For precisions see notes in Tables 7-9 and 7-13

(c) Mass injected at the start of the SGTRs calculated over a 25 second period, that in Test T-1958 during the 250 to 190 in. boildown over 80 seconds.

(d) Secondary dryers bypassed

(e) Equivalent time for 100% bypass, 0.025 sec.

562

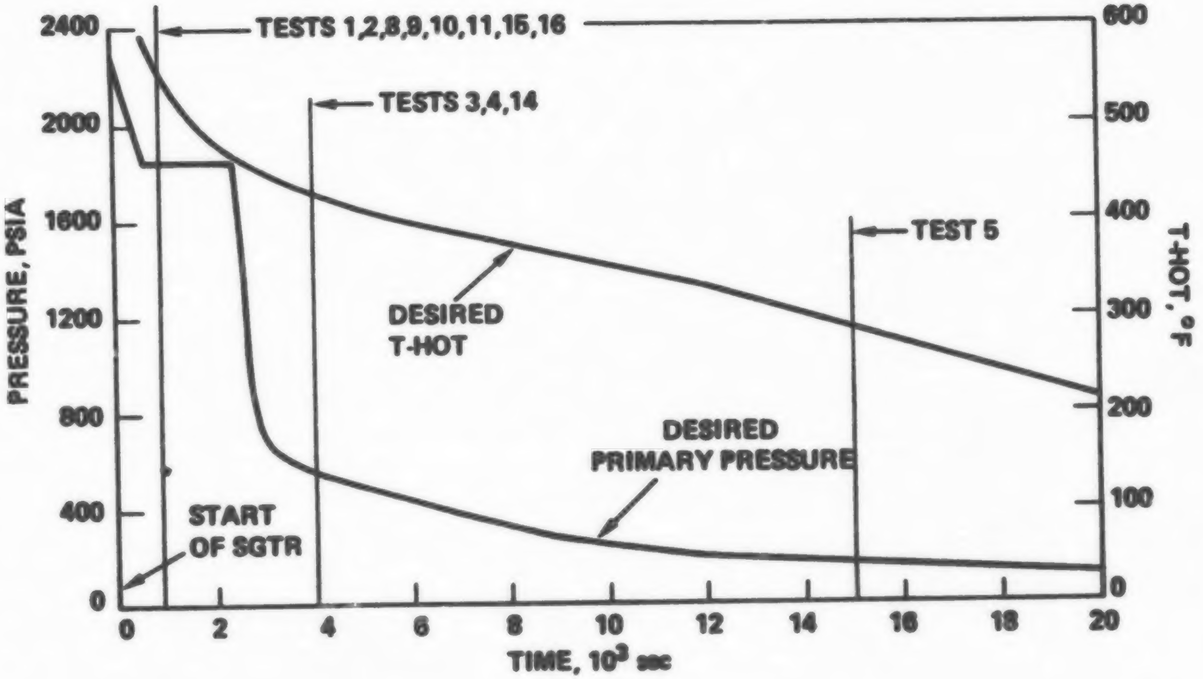

Figure 7-1. Test Transient for 10% SORV Flow with SGTR and Loss of Off-Site Power, (Test No. 12) Showing Conditions for Steady-State Tests

563

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SECTION 8

DISCUSSION AND CONCLUSIONS

8-1. CARRYOVER AND BYPASSING

The principal observation made during the test program was that very little or no primary coolant bypassing was detected under steady-state SGTR/SORV fault conditions, either at normal water level or when the break location was exposed. Under all test conditions, both at low power or at 100% power, moisture carryover was very low, and under steady-state SGTR/SORV fault conditions no significant increase in moisture carryover was detected. Following short-term perturbations, various types of transient releases were identified. Depending on water level and on the type of transient, these could be dominated by either primary coolant bypassing or moisture carryover and could be the equivalent of steady-state releases over many hours. At very low water levels the results showed that a change in behavior occurred. This can be associated with the cessation of recirculation within the model boiler, so that it was operating, in effect, as a once-through unit.

Under the SGTR/SORV fault conditions, steady-state levels of carryover and bypassing were very low when recirculation was maintained, were insensitive to changes in water level from 130 in. collapsed level (the lower limit for maintaining reciruclation) to 495 in. (just below the dryer inlet) and to the bypassing of the dryer. At low power, 2 to 10%, it was difficult to define the absolute carryover level, and at normal temperatures and pressures (1000 to 1080 psia) the observed carryover could have been dominated by the volatilities of lithium or potassium hydroxide. Typically, the observed carryover was of the order of 0.0005%. At lower temperatures and pressures carryover was not detected, < 0.0005%. In most tests, no evidence for steady-state primary coolant bypassing was seen, but in two or possibly three tests, a very small bypass fraction was detected. Again, this level of bypassing was of the order of 0.0007 to 0.0012%. Surprisingly, bypassing was seen only in bottom break tests at lower temperatures and pressures (Tests 4, 5 and 14), and no bypassing was seen in any top break tests (but the latter were not carried out under similarly reduced temperatures and pressures).

At 100% power, steady-state carryover at normal or high water level was also low, 0.001 to 0.002%, but was about three times that found at low power. With the dryer in service, raising the water level to just below the dryer had no effect, but there was a massive increase to 10 to 20% once the dryer flooded. With the dryer bypassed, carryover at normal water level was similar to that with the dryer in service (0.0017 to 0.0023%), but carryover increased to 0.012% when water level was raised to submerge the primary separator. The absence of any increase in carryover on bypassing the dryer may indicate that the MB-2 primary separator and gravity separation were very efficient in removing droplets. However, since the dryer modification effectively increased the gravity separation region to include the dryer entrance plenum and the steam dome, the results could, in part, be also due to an increase in the efficiency of gravity separation.

In a number of tests under recirculating conditions, perturbations to test conditions caused transient releases. These can be collected into three major groupings, namely, sudden increases in steam flow rate, initiation of SGTR break flows, and rapid changes in water level. Of these groups the greatest releases were caused by increases in steam flow rate, either by cycling the safety relief valve (Tests 10 and 11) or by opening the steam lines to promote increased flow (Test 12) or boildown (Tests 10 and 11). When the water level lay between normal water level and the entrance to the dryer, the transients caused only a small carryover release, but a significant degree of primary coolant bypassing. Typically, the bypass release was about 0.5% of the primary coolant injected over an 80 second period, or the equivalent of 100% bypass for a period of 0.4 seconds. At the very low levels of carryover seen in these tests, such a transient could be a major factor in any overall release. For a steady-state bypass level of 0.001%, a transient release equivalent to 100% bypassing for 0.4 seconds corresponds to a steady-state release over 11 hours. Unfortunately, however, no transient due to an increase in steam production rate was studied during a bottom break test, and no data are available on the effect of variation in break location on bypassing. When the water level lay above the inlet to the dyrer, i.e., up to ~ 525 in., transient releases of this type increased in magnitude, up to 0.4% of the total tracer mass in the boiler, but in each case was of bulk model boiler water alone, with no evidence for any preferential bypassing.

Again, such transient releases could dominate the overall releases during a fault. For steady-state carryover at 0.0005%, a transient release of 0.4% of the liquid mass (about 4 lb at normal water level) is the equivalent of a steady-state release over about 120 hours at 10% power with an SORV flow rate of 1.8 lb/sec. The remaining transient releases were of smaller magnitude. In four tests they were produced on initiating the SGTR flow and were mainly due to transient bypassing. Similar releases were seen in the group of tests carried out at low level, once water level had been raised to reestablish recirculation. Of the examples seen, four transients occurred in bottom break tests, Tests 1, 4, 14 and 16, and three in top break tests, Tests 2, 8 and 15. Similar-sized transient releases were also produced by rapid changes in water level. These were seen in Test 2 during boildown and in Tests 8, 15 and 16 on increasing water level to 280 in. All these transients gave releases of bulk model boiler water only and, even though that in Test 2 occurred while the SGTR was in progress, gave no preferential bypassing.

When collapsed water level was reduced below about 130 in., recirculation ceased in the model boiler and it became, in effect, a once-through unit. In Tests 8, 9, 15 and 16 this change was accompanied by a significant change in the type of release observed. In the early stages of these tests, blowdown caused transient releases of 0.4 to 1.3% of the available tracer mass as recirculation collapsed, and this was followed by sustained levels of increased carryover, 0.004 to 0.008%. At later stages in the tests the initiation of the SGTR break flows tended to cause large transient releases of up to 8% of the total liquid mass, as did the subsequent changes in water level. During the SGTR phases the type of transient release was dependent on the break location, at least during the initial SGTR phase. Significantly, there was little or no release in the two bottom break tests, but a large release of secondary side tracer alone in the top break tests. Due to the nature of the transient releases, the steady-state carryover levels were not readily determined, but they appeared to be similarly enhanced in the way seen after blowdown. In no test, either top or bottom break, was there any evidence for a significant level of primary coolant bypassing. A detailed analysis of the group of tests, see Sections 7-2 and 7-3-2, indicates that the dominant mechanism for the transient releases was the transfer of the tracers onto the dry surfaces of the tube bundle in regions where this was generating superheated steam, followed by their release on rewetting the surfaces.

In three further tests the transient releases described above were not seen. These were when recirculation collapsed as water level was reduced in Tests 10, 11 and 14, and when the SGTR break flow was restarted in Test 14. Significantly, the available heat transfer was less in these tests, superheat levels lower and evidence for hideout of the type described above absent. Moreover, in Test 14 there was no evidence for any sustained level of increased carryover under these conditions. In Test 11, increasing the steam flow rate at very low water level gave a large transient release.

The analysis of these overall results can be separated into two steps. Firstly, there is a need to explain the generally low levels of carryover and bypassing under all conditions and the transient releases observed. Secondly, there is a requirement to consider if the results can be applied directly to faults in Model F and other steam generators, or whether the results need to be scaled and, if so, by how much. These aspects are considered below.

Sources of Fine Drops for Carryover

The observed carryover at low power was very low in all tests, generally about 0.0005% when recirculation was maintained and 0.003 to 0.008% when there was no recirculation (both at normal secondary temperatures and pressures as in Tests 8, 9, 15 and 16; carryover decreased further at lower temperatures and pressures). It is improbable that this carryover could arise from the tail end of a unimodal drop size distribution created by the two-phase flow system and it is more probable that it will arise from some special mechanism capable of producing fine drops that would escape collection by either the primary separator or dryer. In addition, at very low water level, it will be necessary to explain how the mechanism can gain access to salts present in the model boiler so that the various transient releases can be explained.

It has long been known that bubbles come to rest at liquid-vapor interfaces and take on a lenticular shape. The top of these are enclosed by thin liquid films, which drain, thin and finally break. The discharge of the enclosed vapor creates a cloud of micron-sized drops. The cavity left behind in the liquid surface rapidly fills and this may eject several drops of substantially greater size. Here we are concerned with the small drops from the liquid film, and data on these are available from geophysicists, as such drops are the source of salt nuclei from the sea and are important in the seeding of clouds.

The number of fine drops, N, produced by the bursting of bubble domes with diameters up to 3 mm in distilled or sea water were counted by Day and Lease (1), who found that

$$N = 2.9 \times 10^4 \, d_f^{2/3} \qquad (8\text{-}1)$$

where d_f is the dome diameter in meters.

There are much less data on the size of the fine drops produced. Blanchard and Syzdek (2) measured the size distribution produced by bursting bubbles of 0.74 mm in diameter. These gave log normal distributions with mass median sizes of 7μm and approximately 8 drops per bubble. Day and Lease showed that the diameter of the exposed bubble dome would be 0.07 mm, from which equation 8-1 gives 49 drops per bubble. However, Day and Lease burst bubbles into a supersaturated atmosphere to prevent loss of drops by evaporation, and it must be concluded that there were many fine drops of less than 1μm, which were undetected in Blanchard and Syzdek's work. Such fine drops would not contribute greatly to the mass.

Cipriano and Blanchard (3) indicate that bubbles of 4.5 mm diameter produce 170 drops per bubble with sizes ranging between 2 and 6 μm, equivalent to a mass median size of 4 to 5μm. For these bubbles the diameter of the exposed bubble dome would be about 3.4 mm, for which equation 8-1 predicts 650 drops per bubble. Since the bubble sizes considered in the boiling process below are of about this size and because most of the mass will be in the drops detected by Cipriano and Blanchard, the numerical coefficient in equation 8-1 will be divided by four and the mass median drop size will be assumed to be between 4 and 5 μm. This makes no allowance for the change in physical

568

properties to steam and water under pressure, because no justifiable allowance can be made.

We may now assume that all the steam produced in the boiler bursts as bubbles of suitable size and estimate the carryover, assuming further that 5 μm drops will not be removed at any stage. However, it is of interest first to consider boiling from thin, draining water films because, especially when there is no recirculation, these may be expected to be present in the upper parts of the boiler. It should be noted that the steam velocity is low and will not substantially affect boiling under these circumstances, except that the steam will carry away fine drops. Kusada and Nishikawa (4) studied boiling from thin stationary water films on horizontal surfaces and showed that steam domes up to 50 mm diameter can form. Steam bubbles beside projecting above the water level as domes, penetrate the water film and evaporation occurs from a microfilm on the heating surface; the microfilm may even dry out. More relevant data were provided by the studies of Petrovichev, Kokorev, Didenko and Dubvrovskiy (5) and Fujita and Ueda (6), who observed bubble domes forming and flowing down with a boiling liquid film on a vertical tube. The latter found that the domes had diameters between 5.2 and 6.4 mm, which is about twice the Laplace length scale of $[\sigma/\Delta\rho g]^{1/2}$, where σ is the surface tension, g the acceleration due to gravity and $\Delta\rho$ the density difference between the phases. It is also about the size of bubbles found in nucleate pool boiling. Here we will use this value and assume a hemispherical bubble in boiling from a thin film. This may now be used with equation 8-1, with the numerical coefficient divided by four to give the carryover, w,

$$w = 2.9 \times 10^3 \, d^3 \left[\frac{\rho_w}{\rho_s}\right] \left[\frac{\Delta\rho g}{\sigma}\right]^{7/6} \qquad (8\text{-}2)$$

where d is the mass median diameter of drops, ρ_w is the water density, ρ_s is the steam density and SI units are used. A substantial change would not be expected if the general boiling process is considered, where bubbles similarly have to burst.

If we assume that $d = 5$ µm, then at 1080 psia (74.5 bar) equation 8-2 gives $w = 2.5 \times 10^{-5}$ (0.0025%). This is five times the value observed typically at normal water level in MB-2, but considering the many uncertainties that have been stressed with respect to numerical values, this must be regarded as good agreement. It is possible that some of the largest of the fine drops would be separated and if that reduced the mass median diameter by a factor of two, carryover fraction would fall to 3×10^{-6}. We may further note, since the carryover is produced by the bursting of bubbles at the liquid-vapor interface, that the quantity of fine drops produced should, as an approximation, be proportional to the number of bubbles being produced, which, again, as an approximation, should be proportional to the steam flow. Thus, for this mechanism, the carryover expressed as a weight fraction of the steam flow rate should, to a first order of approximation, be independent of the steam flow rate. However, some variation with power is not unexpected and an increase in carryover by a factor of between two and three as power is raised from 10% to 100% is reasonable. It should be noted also that the mechanism is essentially independent of water level and the insensitivity to this parameter is also explained, and that carryover should decrease as the secondary pressure falls due to the decrease in heat flux and steam flow rate. We may conclude then that there is a strong possibility that the observed carryover is due to the fine drops produced by the bursting of bubbles. It is of interest to note that Petrovichev, Kokorev, Didenko and Dubvrovskiy (5) and Fujita and Ueda (6) both collected spray formed from the boiling process and deposited nearby. Similar results were obtained, with the latter authors concluding that the rate of spray volume to bubble volume was a simple constant of 6.2×10^{-4}. This is equivalent to ten 160 µm drops from a 3 mm hemispherical bubble or to carryover of about 10^{-2} at 1080 psia. This merely emphasises that carryover probably arises from a small part of the volume of drops produced in a bubbling process, though the number of drops concerned may be a large proportion of those generated.

The picture that emerges is that a carryover fraction of 5×10^{-6} at water levels when there is recirculation is reasonably accounted for. When recirculation stops and part of the tube bundle is exposed above the general water level, water will be splashed up from the water pool and will drain back to the pool as thin films on the tube surfaces. Entrainment from those films due to boiling may be easier than from boiling in the pool. At least, entrained fine drops will be less easily separated than in the churning steam-water system in the pool. Therefore, the overall level of carryover may be greater than when there is recirculation. The same argument explains the transient carryover observed when recirculation ceases, when a large area of tube surface will be covered by a water film draining back into the boiling pool.

If we now consider the state existing once recirculation has ceased and when the boiler is acting as a once-through system, we have a situation where there is a boiling pool of liquid with above it a large tube surface area. Some of the area will be dry and locally producing superheat in the steam passing over the surface. As described above, there will be water splashing up and draining, but above that level, some water spray can dry out on the tube surfaces and leave deposits of dry salt. Clearly, the degree to which the latter can occur will depend on the steam flow rate, the available heat transfer at the tube surface and on how long operations are maintained under these conditions. When water level is raised, access to this dry salt will be gained by water splashing up from the pool and draining. This will account for the transient releases under these circumstances. It also will account for the transient releases of lithium when the top break SGTR, containing only potassium, was started and when the injected water gains access to the dry salts as it falls back onto the tube bundle. In bottom break tests access to those deposits cannot occur and no release was seen. In the later SGTR phases, transient releases of both lithium and potassium were seen, but here only a limited area of tube surface was available on which salts could dry out and presumably this was accessible during both top and bottom breaks.

Finally, in all low level tests, transient releases gave a slow exponential decay in carryover, even in the transient following the increase in water level to reestablish recirculation in the model boiler. This and other details of the experimental results are examined in more detail below, so that we can be sure that they are consistent with the general picture outlined above.

571

Injection of SGTR Break Water

During the SGTRs the primary coolant injected into the model boiler will flash as it discharges and such a process usually produces fine water droplets. The fraction present as fine drops, say < 10 μm diameter, will not be removed by the separator or dryer and should escape with the SORV steam. This consideration was the origin of the postulates for primary coolant bypassing and it is surprising that it was not seen, but the data unambiguously show that bypassing was absent or present only at very low levels.

The droplet sizes produced from jets flashing through orifices of 0.25 to 3 mm diameter and at temperatures up to 145°C were measured by Gooderum and Bushnell (7). The results, and those of others show a log normal droplet size distribution where the Sauter mean diameter, d_s, can be correlated by,

$$d_s = D\,e^{(-0.422-0.0207T)} \qquad (8\text{-}3)$$

where D is the orifice diameter (mm) and T the upstream temperature (°C); there was no influence of downstream temperature. In the current tests D was about 2.4 mm and T ranged from 162 to 304°C, so the correlation must be extrapolated to higher temperature. The calculated mean diameters are: Test 5 (162°C), 55 μm; Test 3 (219°C), 17 μm; Tests 4 and 14 (240 to 244°C), 10 to 11 μm and Tests 8, 9, 15 and 16 (304°C), 2.9 μm.

Since the mean size is predicted to fall on increasing temperature, it might be expected that bypassing would become more significant as the primary temperature increased. In fact, the opposite trend was apparent and bypassing was only detected at lower temperatures though, even then, it was only at very low levels. It should be noted that there is no experimental evidence available on the size of drops produced by the flashing of water jets at the experimental conditions of interest here. In particular, these involve flashing to a high secondary side pressure, such that the steam voidage produced immediately upon flashing varied between 0.5 and 0.84. When it is noted that a randomly dumped bed of unform spheres has a voidage of about 0.4, it is probable that substantial agglomeration of fine drops, even if they were produced in the first place, would occur. It is then not unreasonable that bypassing would only become apparent at the higher flashed voidages, which

572

here occurred at the lower primary water temperatures. Confirmation of this hypothesis could only come from suitable experimental work, but this would not alter the unambiguous conclusions of the present tests regarding bypassing.

Flow Conditions at Very Low Water Level

In Tests 8, 9, 15 and 16 circulation rates fell as water level was reduced and, on the basis of the S-1 sample line behavior, circulation ceased at a downcomer water level of about 130 in. This implies that there was an essentially stagnant pool of water with a definable interface and the first step is to determine if this is probable when taking into consideration the fact that such an interface is no longer definable if the voidage rises above a value of between 0.7 and 0.8.

Gardner (8) correlated a large body of information on the voidage, α, in liquid pools with the expression,

$$\frac{\alpha}{(1-\alpha)^{1/2}} = 11.2\, F^{2/3}\, P^{0.2} \qquad (8\text{-}4)$$

where

$$F = \frac{\rho_w^{1/2}\, U}{(\Delta\rho g \sigma)^{1/4}} \qquad (8\text{-}5)$$

and

$$P = \frac{\rho_s \nu_w^2 (\Delta\rho g)^{1/2}}{\sigma^{2/3}} \qquad (8\text{-}6)$$

where ρ_w and ρ_s are the water and steam densities, $\Delta\rho = (\rho_w - \rho_s)$, ν_w is the kinematic viscosity of water, σ is the surface tension, g is the acceleration due to gravity, and U is the superficial steam velocity. For Tests 8, 9, 15 and 16 the value of U at the top of the tube bundle was 0.48 m/sec (and was 0.30 m/sec above the tube bundle). It will be assumed that it has the same value at the top of the liquid pool, although some evaporation will occur above this level. At 1075 psia (74 bar), $F = 3.98$ and $P = 2.25 \times 10^{-8}$ and hence

573

$$\frac{\alpha}{(1-\alpha)^{1/2}} = 0.83 \tag{8-7}$$

from which $\alpha = 0.555$. This result is strictly only applicable to pools of large diameter and needs to be modified somewhat for use with pools having small hydraulic diameters, since it is known that the influence of the walls of a tube is to increase voidage. This was recognized by Sterman (9) and is shown by the work of Behringer (10) and Filimonov et al. (11) in tubes of 57 to 82.5 mm bore. Examination of the latter data and also some unpublished data on boildown in PWR fuel bundles indicates that the effect of the tube walls can be accommodated by multiplying the voidage given by equation 8-7 by a factor of 1.2. Assuming that this correction factor is applicable here, $\alpha = 0.665$. Hence it appears that a definable water level is probable in these tests, though the steam production rate might not have to be increased by too large a factor for this to cease to be true.

Applying the correction factor of 1.2, the right hand side of equation 8-6 now becomes 1.15. From this, it is then a simple matter to estimate the swell of the water pool by a simple integration, if it is assumed that the steam is generated uniformly up the height of the pool. The average value of the voidage is,

$$\alpha_a = \int_0^{1.15^{3/2}} \frac{[(x^{8/3} + 4\,x^{4/3})^{1/2} - x^{4/3}]\,dx}{2\,(1.15^{3/2})} \tag{8-8}$$

which evaluated numerically gives $\alpha_a = 0.463$. Therefore, the downcomer level should be multiplied by 1.86 to give the interface levels in the boiler. For downcomer levels of 60, 104 and 160 in. the interface levels are 112, 193 and 298 in., respectively.

The validity of the above analysis can be checked by the density measurements reported in Section 6. The results at downcomer water levels of 62, 106 and 152.5 in., reexpressed as voidage and normalized in terms of height in the boiler divided by downcomer level are shown in Figure 8-1. From this it is seen that this method of plotting reduces the data to a satisfactory single experimental curve. A theoretical curve is also given where, for example, voidage is 0.665 at the reduced height of 1.86. Agreement between theory and experiment is fair and shows that conditions within the boiler when circulation has stopped is in accord with normal expectation. For this simplified approach better agreement is not expected, for, besides any faults in the theory, discrepancies may be due to a number of factors such as nonuniform generation of steam with height and the substantial nonsymmetric generation of steam between hot and cold legs. These factors were not included in the current analysis as they would not significantly modify the overall description of the conditions existing within the boiling pool.

From the data given in Figure 8-1, a voidage of about 0.975 exists at a reduced height of 2.5, where this level of voidage corresponds to a quality of 0.68. Applying this factor to a downcomer level of 130 in. predicts that this quality would exist at about 325 in. This is close to the inlet to the riser to the primary separator at 340 in., and it is reasonable that circulation should cease at about this level. We assume here that the height of the riser can be ignored, as steam velocities will increase substantially in the riser and will carry any moisture up to the primary separator.

If we now examine the data at a downcomer water level of 62 in., as shown in Figure 8-1, we see that there are only four data points. Those for the two lower levels are consistent with the rest of the data, but the others have appreciably higher voidages. These are consistent with the concept that there is a liquid pool up to a voidage of 0.7, corresponding to a level of 70 in. and that water splashed up above this level separates out on the tube surfaces and on the tube support plate at 80 in. and is virtually eliminated from the steam at a level of 100 in. In other words, there is a splash height of about 30 in. The data for a downcomer level of 104 in. is, in this respect, less certain but it is consistent with a liquid pool up to a voidage of about 0.8 at a level of 190 in. with a splash height of about 50 in. to a height of 240 in., still within the tube bundle.

The inferences of the last paragraph support the view that there will be draining water films extending 30 to 50 in. above a water pool when water level is low and, if boiling from these films will give additional carryover, then the greater carryover observed without circulation is explained. As a corollary, at a downcomer water level of 62 in. the tube bundle above 190 in. should be essentially dry and can be expected to generate superheated steam within the bundle. At a downcomer level of 104 in., the corresponding level is 240 in. Both results are in agreement with the superheat observed in the tests at these water levels. Finally, if these dried-out surfaces above the splash height collect dried-out salts, these would be released as carryover through boiling from draining films when the level was raised.

To reinforce the idea of a splash height it is useful to look at the correlation of Sterman (9) for the critical height, H, to which substantial quantities of water are carried above a water pool through which steam is being bubbled. Sterman examined data on water being sampled at various heights and found a sharp break in the curve of the variation of water concentration versus height at the critical height; above this level water concentrations fall only slowly. The correlation is:

$$\frac{H}{L} = 9.12 \times 10^{5} F^{1.2} P^{0.55} \left[\frac{\Delta\rho}{\rho_w}\right]^{0.6} \left[\frac{\rho s}{\Delta\rho}\right]^{0.19} \qquad (8\text{-}9)$$

where

$$L = \left[\frac{\sigma}{\Delta\rho g}\right]^{1/2} \qquad (8\text{-}10)$$

and the other terms are as have been defined above. At 1075 psia (74 bar), L = 1.56 mm, P = 2.25 x 10^{-8} and, with a superficial steam velocity of 0.48 m/sec, F = 3.98. Thus H is 30.6 in., in good agreement with the observations made above. However, it should be noted that Allis Chalmer (12) gave a different correlation for their own data where,

$$\frac{H}{L} = 4.21 \times 10^{10} F^{2.38} P^{1.52} \left[\frac{\rho_w}{\Delta\rho}\right]^{0.6} \left[\frac{\Delta\rho}{\rho_s}\right]^{1.4} \qquad (8\text{-}11)$$

which gives H = 10.3 in. In this correlation the very different exponent in F, which contains the steam velocity, is surprising.

Sterman (9) also correlated carryover at the critical height, H, and found that

$$w = 1.19 \times 10^{-4} \rho^{-0.165} [\frac{\rho_s}{\Delta\rho}]^{0.461} \qquad (8\text{-}12)$$

Here, this gives a carryover of 5.76×10^{-4} (0.058%), which will decrease slowly with height. This value is about an order of magnitude greater than found in the present tests. Since no difference was observed when the dryer was bypassed, it would imply that the reduction in carryover observed was due to the effect of the primary separator.

Transient Releases When Circulation Collapses

In the blowdown phases of Tests 8, 9, 15 and 16, at the final downcomer water level of about 50 in., the splash height would reach about 125 in., leaving the top 145 in. of the tube bundle exposed. Each of the 52 tubes has an exposed length of about 300 in. and, since the tube diameter is 0.6875 in., the total surface area is about 22 m^2.

We may also calculate the thickness of a water films that can be held stationary in a rising steam flow, in order to calculate the quantity of salt that could be available for release as the film boils away. In the present cases the hydraulic diameter of the passages in the tube bundle for steam flow is 0.0276 m, and with a steam velocity of 0.48 m/sec. this gives a Reynolds number of 27000. With a friction factor of 0.006, the shear stress, τ, exerted on the tube wall (friction factor times the steam velocity head) is 0.027 kg/m sec^2.

The thickness, h, of a liquid film on a vertical surface for which there is no net flow is given by,

$$h = \frac{3}{2} \frac{\tau}{\Delta\rho g} \qquad (8\text{-}13)$$

This formula assumes viscous laminar flow and here gives h = 5.9 μm. For a 22 m^2 surface area this corresponds to 0.095 kg of water. At a concentration of about 50 ppm lithium (50 mg/kg), and making no allowance for concentration during blowdown, the quantity in the liquid is about 4.7 mg lithium.

In the tests the quantities released were in the range of 20 to 40 mg lithium (omitting Test 15 at lower tracer levels) and were observed over periods of 10 to 20 minutes. Considering all the uncertainties and assumption, including the effects of concentration during blowdown, the values compare favorably. One would expect that at least some of the salt in the hanging liquid film left after drainage to dry out and be left on the tube surface. Equally, however, one would also expect there to be some carryover before the film reaches the thickness predicted by equation 8-13.

For these tests a further calculation reinforces this last conclusion. Jeffreys (13) showed that the thickness, h, of a liquid film left behind at time, t, at a distance, x, from the top of a draining vertical surface is given by,

$$t = \frac{\mu_w x}{\Delta\rho g h^2} \tag{8-14}$$

where μ_w is the liquid dynamic viscosity. No shear from the steam flow is considered, but it is of interest to calculate the time to achieve the thickness of 5.9 μm for x equal to half the draining height of the tube bundle, i.e., 1.84 m. This time is 700 sec. Such a value is in agreement with the experimental results, though the estimate is confused to some extent by the continuation of blowdown after recirculation had ceased.

We must now consider the three tests, Tests 10, 11 and 14, where the collapse of recirculation was not associated with a transient release. In submerged nucleate boiling all the heat transferred generates bubbles which may then progress to the steam-water interface to burst and thus produce fine drops for carryover. The carryover as a fraction of steam produced may then be expected to be fairly independent of heat flux. Circumstances are different when boiling from a thin draining film, such as would occur above the water level in the MB-2 tests and which might occur, to a lesser extent, for some distance below the water level. Here the opportunity arises for heat to pass into the

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water film and cause evaporation from the main film-steam interface. A simple model is that a draining film has no more than a certain capacity to evaporate in this fashion. Once a certain wall superheat is exceeded nucleation sites will be activated, tending to control the superheat. If the heat flux is increased, more nucleation sites will be activated and the superheat will only rise marginally, so that the heat transferred to give interface evaporation will not change substantially.

Fujita and Ueda (6) used this model to deduce the amount of liquid entrainment volume per unit steam bubble volume. A consequence of the argument is simply that the carryover may be expected to fall dramatically as the critical heat flux for nucleation is approached with falling heat flux. According to Fujita and Ueda, as well as Petrovichev, Kokorev, Didenko and Dubvrovskiy (5), the critical heat flux at atmospheric pressure is about 0.1 MW/m^2. There is no way of relating this to local conditions in the MB-2 tests, but a decrease in the magnitude of the transient releases (as well as a decrease in steady-state carryover from wetted tubes) is to be expected as the measured superheat in the tube bundle falls.

Transient Releases

When recirculation was maintained, three forms of transient release were found. Of these the most significant was that caused by a sudden increase in steam flow rate, such as when the safety relief valve opens. This type of release can be ascribed to the sudden increase in steam production rate, which will cause swell in the boiling fluid and additional frothing. This may be expected to give a transient release, the magnitude of which should increase as water level increases, although the time constant for the transient may be expected to differ for different systems depending on the thermal-hydraulic response of the system. In the present tests, at water levels below that of the dryer, the top break SGTR gave an associated transient primary coolant bypass release. Expressed in a form which is independent of the time constant for the thermal-hydraulic response, the release was typically equivalent to 100% primary coolant bypassing for 0.4 sec. As this top break location was designed to maximize bypassing, some reduction in bypasing may be expected for SGTR break locations within a tube bundle.

579

The second group of transients, principally due to transient primary coolant bypassing, was associated with the start of the SGTR break flow. These transients were of lesser magnitude, equivalent to 100% bypassing for 0.02 seconds, and were probably due to the initial surge as the break flow commenced. Even though no corresponding change in steam production rate occurred, the transients must similarly originate from a change in the swell and frothing in the boiling pool. The final type of transient in this group was that caused by rapid changes in water level. Of this group, that caused by boildown probably has a similar origin to the releases produced when recirculation collapses, while those when level was raised were presumably due to the increase in the quantity of auxiliary feedwater entering the base of the boiling pool and to the disturbance that this change creates.

When recirculation was absent, much larger transient releases were seen. As described earlier, most of these were almost certainly caused by the rewetting of dry surfaces covered with salt deposits, either when the break flow was initiated or as level was raised. Typically, these transients showed a large initial increase in concentration in the SORV condensate, followed by a slow exponential decay. Here we will not consider the magnitude of the releases, for they will be related to the quantity of salt available for release, which in turn will be related to the rate of transfer from the boiling pool and to the period over which the salt had been accumulated. Both these will be test specific and in the real case would be fault specific. We note only that under the less vigorous conditions of Test 14, with lower steam flow rates, lower heat fluxes and measured superheat, the transient release was much reduced. Indeed, in this test the release on restarting the SGTR break flow was probably of a similar type to those seen at normal water level on starting the break flow, but was of greater magnitude, a 30-fold increase, as might be expected at this low water level. A similar enhancement was seen in the single transient produced on increasing the steam flow rate at very low water level, but here with a top break there was about a 100-fold increase in the release.

At first, it is puzzling that carryover decays rather slowly once it has peaked after a level change or when recirculation restarts, because the salts concerned would dissolve rapidly. Since, from Tables 7-15 and 7-16, the total quantities released are small, it is probable that the release is from salt which has hidden out in crevices within the model boiler. When dry surfaces exist in the tube bundle, such crevices exist within the tube support plates and if these trap solid salts, one might expect that leaching would be slow. Indeed, rewetting would only let in water slowly, because boiling would be occurring, and the bursting of bubbles due to this boiling might be an efficient mechanism for entraining the salt in fine drops. However, while this may explain the slow decay at low water levels, once recirculation is reestablished any support plate crevices will be submerged and there should be much more rapid access to any salt. This then suggests that other crevices may be implicated in the decay and this may well be the case in view of the number of crevices that exist elsewhere in the model boiler, particularly in the upper shell and separator assemblies.

8-2. APPLICATION TO FULL-SCALE STEAM GENERATORS

Although the principal value of the present MB-2 data is the identification and quantification of the processes responsible for droplet carryover during SGTR faults and the provision of data of sufficient detail and accuracy for use in developing and verifying physical models (usually computer codes) for these processes, the data may also be compared with full-sized units to identify any systematic differences in carryover. For this, two major aspects need to be considered. These are (a) whether there is a need to scale the current data to make it applicable to full-sized units and (b) whether the data allow for the extrapolation of existing plant carryover data to low power for use under SGTR fault conditions. These aspects are considered in this section and are intended to highlight those areas which will need to be considered in any physical models or computer codes developed for use with full-sized units.

Steam Generator Under Recirculating Conditions

Nuclear power plant steam generators are generally warranted to produce steam with a moisture content of less than 0.25 percent by weight. In practice, at 100% power, plant performance has been variable, with the different designs of separators and dryers giving moisture carryover at up to or beyond the warranted value (14, 15, 16). Tests have shown that the performance of the swirl vane primary separators can be improved by modifications such as the addition of a hydraulic skirt around the separator outlet deck plate (mid deck plate), the provision of additional drains and vents, the extension of the the separator outlet orifice to form a collar above the mid deck plate, an increase in the size of the separator outlet orifice and the provision of perforations in the riser barrel beyond the separator (14, 15, 16). These modifications are primarily designed to reduce the froth believed to form on the mid deck plate, generated by the vapor jets issuing from the separator orifices, and to improve separation by taking advantage of the liquid film which should form against the riser barrel wall beyond the separator swirl vane (14, 15). In addition to improving separator performance, improvements may also be made in the dryer performance, but in practice these have been restricted to improvements in the drainage capacity, to prevent reentrainment due to the overfilling of the dryer drip trays (16). In Model 51A steam generators such improvements have reduced carryover at 100% power from 0.25% to 0.04% (16).

In the present tests the MB-2 model boiler was designed to provide overall prototypical thermal-hydraulic behavior for a Westinghouse Model F steam generator. However, exact prototypical behavior cannot be expected in every aspect of its performance and this will apply particularly to moisture carryover. While the modular separator used in the MB-2 was an exact duplicate of the primary separators in Turkey Point 3 and 4, some of the field unit primary separators may "see" much higher than average steam loading owing to uneven flow distribution in full-sized units. Furthermore, the use of a single primary separator in the test model necessitates an appportioned steam shroud between the primary and secondary separator. This introduces a large surface-to-volume ratio between these components, which could possibly result in enhanced separation upstream of the dryer. It should be noted also that there are some differences among the Model F field unit primary separators themselves; while all have extensions to the separator outlet orifice, only the modular and the 2- and 3-loop units have perforations in the riser above the swirl vane. These differences between the MB-2 and the field units may explain the improved moisture separation seen in MB-2.

582

To assess the present results, a comparison at 100% power may be made with plant data obtained on Model F or 44F steam generators. At 100% power data are available on five units, Kori 2, a two loop station operating at higher steam flows (17), Wolf Creek (18), Callaway (19) and Turkey Point, Units 3 and 4 (20). The latter, although 44F units, are particularly relevant here as they contain identical modular primary separators to that incorporated in the MB-2 model boiler. The data for these stations gave carryover values of 0.08% (Kori 2), 0.015% (Wolf Creek), 0.0135% (Callaway), 0.016% (Turkey Point, Unit 3) and 0.012% ave., 0.015% max. (Turkey Point, Unit 4) at 100% power. These vaues are an order of magnitude higher than those seen in the present tests, but we note that they were obtained using sodium-24 radio-tracers and may not have the precision or discrimination of the MB-2 results. Typically, such sodium-24 measurements will only detect carryover above about 0.005%, compared with a limit of detection in the present tests of 0.0002 to 0.0003%.

It is difficult to identify the origin for the differences in carryover, but some indication may be obtained by considering the quantity of moisture removed by the dryer. In the current series of tests, virtually identical results were obtained both with the dryer in service and with it bypassed, which may imply that virtually no moisture reached the dryer (see above). This result differs from that obtained with the earlier instrumented bundle (see 21, Figure 2-1a), which had a different primary separator/deck plate configuration and where the moisture removed in the dryer was ~ 0.8% at 60% power, ~ 2.5% at 100% power and ~ 10% at 130% power. It also differs from the value found at Wolf Creek, where up to 9% moisture was removed by the secondary dryers at 100% power (18). These differences suggest different primary separator efficiencies in the three cases.

If we consider the MB-2 results, the conclusion reached is that carryover is due to the fine drops produced by bubble bursting; drops that will pass through the separator without loss. This fraction will not be affected by changes in geometry, surface area, etc., and should not alter greatly in a full sized unit. However, fine drops may also be generated by other processes and, in particular, could be generated from the type of froth postulated to form on the mid deck plate (14, 15). Although there is no direct evidence to

583

indicate that such a froth forms in a Model F unit, the removal of up to 9% moisture by the dryers at Wolf Creek would suggest that such a froth may be present.

Overall, the conclusion reached is that the MB-2 data at 100% power are not prototypical of a Model F steam generator and that there probably exist other mechanisms for producing fine droplets in addition to that proposed in this report. Such mechanisms will need to be identifed and modelled in any overall mechanistic model. Until validated mechanistic models for incorporating all mechanisms for producing fine droplets have been developed, in practical use it follows that the MB-2 data should not be used directly at full power and that any calculations of release should be based on measured plant values. For Model F type steam generators the data indicate a value of 0.015%, a factor of ten increase over the MB-2 results. Other values may be appropriate for other steam generator designs.

At 10% power the current MB-2 data show a reduction in carryover by about a factor of three from that at 100% power. More importantly, the data also show minimal primary coolant bypassing and that no increase in moisture carryover occurs under SGTR/SORV fault conditions. For primary coolant bypassing no data exist with which the present data may be compared. Although the question of scaling will need to be addressed in any mechanistic model for activity release, it is unlikely that primary colant bypassing will differ substantially in a full-sized unit, since similar mechanisms for agglomeration and removal may be expected to operate. In the interim, it is suggested here that the MB-2 value of approximately 0.001% primary coolant bypassing should be used for SGTR/SORV faults under steady-state conditions.

The observation that moisture carryover does not increase significantly during SGTR/SORV faults enables comparisons to be made between the MB-2 data and plant and experimental data on moisture carryover, and, from this, for recommendations to be made for SGTR/SORV faults. Experimental data show that swirl vane separators (14, 15, 16) or separator/dryer combinations (22) increase in efficiency as steam flow rate, or power, decreases. For efficient systems the improvement in efficiency was similar to that seen in the present tests, but for less efficient separators the improvement was much greater so that at low power all the swirl vane separators tested gave similar results of about 0.05% carryover (14, 15, 16). The earlier MB-2 data quoted above (21, Figure 4-20) show a similar trend. In-plant data are limited (13, 16, 22), but generally carryover is known to decrease with power and, from extrapolations and measurement, should fall below 0.005% once power is reduced below about 60%. Generally, these results are expected, for not only will gravity separation become more efficient as steam flow rates fall, but other mechanisms for producing fine drops (e.g., froth formation on the separator deck) will also become less important. Overall, one may expect carryover to fall towards that seen in the present data and for the MB-2 data to become more prototypical at lower power. However, until this aspect of the MB-2 data has been considered in detail, we recommend here that a conservative approach should be followed and that the MB-2 results should be increased by a factor of ten for use with full sized units at low power. Thus, for 10% power and for SGTR/SORV faults it is suggested that moisture carryover should be taken as 0.005%.

Short-term perturbations gave releases of variable magnitude depending on their type and on water level. The most significant here were those caused by cycling the safety relief valve, where both transient carryover of bulk liquid and transient bypassing were seen, depending on the water level. At high water level the maximum carryover seen was 0.4% of the total bulk water mass, while at normal level the amount of bypassing was equivalent to 100% primary coolant bypassing for 0.4 seconds. We note that both limiting values, while small, are the equivalent of steady state carryover and bypassing for periods of the order of 100 and 10 hours, respectively. In transferring these results to a full sized steam generator, no justification exists at present for the use of any particular scaling factor, nor can it be assumed that the magnitudes of the transients or the relative contributions of primary coolant bypassing and carryover are the same as was found in the present tests. This view is reinforced by the differences already noted between steady-state carryover in operating plant and the MB-2 tests. The more detailed considerations needed to assess such factors and the magnitude of the impact on the total activity release are outside the scope of this report, but clearly, there is a need to use the MB-2 data to develop validated mechanistic models from which the contributions of transient releases can be calculated.

The present data indicate that these transient releases will be important in determining the total releases during an SGTR fault.

Steam Generator at Very Low Water Levels

In the current MB-2 tests at low water level with no recirculation, conditions typical of an early stage in an SGTR/SORV fault (Tests 8, 9, 15 and 16) gave an increase in carryover by a factor of about ten over that at normal water level, but little enhancement in carryover at intermediate stage SGTR/SORV conditions (Test 14). For both it is concluded that the relase is again due to bubble bursting, with the different carryover in Test 14 being due to a fall in temperature, pressure, steam flow rate, splash height and in heat flux necessary to cause boiling in thin films. Transient releases associated with these conditions also differed, depending on the rate and available time for accumulating salts on the dry tube surfaces.

For use with full-sized units an assessment of scaling factors will again be required. More importantly, however, the present data show that it will be necessary to consider the fault sequences in detail before applying the data, as the effects will, in practice, depend on the thermal-hydraulic conditions existing at the time when recirculation ceases and the bundle begins to dry out. Thus, the effects seen in SGTR/SORV faults in the absence of auxiliary feedwater may not be great if the tube bundle only uncovers at a later stage in the fault, when temperature, pressure, steam flow rate and heat flux are low, but it may be more significant in faults where the level falls more rapidly. Of course, in these faults such considerations only apply to droplet release mechanisms and do not address any additional effect due to iodine volatility under these conditions.

Comparison with Radiological Release Calculations for SGTR Faults

Currently for U.S. PWRs, design-base calculations cover only an isolated SGTR fault, occurring when offsite power is or is not available. For this fault, complete severance of a single steam generator tube is assumed and the radiological consequences are calculated for the sequence when offsite power is unavailable. In this case, steam will be discharged from the faulted steam

586

generator for a period of up to 30 minutes via the safety relief valves or the power-operated relief valves. This part of the fault sequence has similarities with the SGTR/SORV and SGTR overfill tests studied in the current tests and the present data may, therefore, be compared with the assumptions used in the radiological release calculational procedure.

For SGTR faults, the current calculational procedure is given in NUREG-0800, Section 15.6.3 (23). In this procedure it is assumed that a fraction of the iodine in the primary coolant escaping to the secondary system will become airborne immediately due to flashing and atomization. Credit may only be given for "scrubbing" of iodine contained in the steam phase and in the atomized primary coolant suspended in the steam phase for release points which are below the steam generator water level. The fraction of primary coolant which does not become airborne immediately is assumed to mix with the bulk steam generator water and to become airborne at a rate determined by the steaming rate and the iodine partition coefficient. An iodine partition coefficient of 100 between steam generator water and steam is conservatively assumed, unless reasonable evidence is available to justify an alternative value.

For this procedure, the fraction flashed is the equivalent of the type of release defined as primary coolant bypassing in the present MB-2 tests. The partition coefficient for iodine recommended is that derived for use under normal operations (14) and is ultimately derived from the partition coefficient for hypoiodous acid determined by Styrikovich (25). Implicitly, this approach assumes that all iodine is present in elemental form (I_2) and that this, at trace quantities, has hydrolyzed completely to equal quantities of hypoiodous acid and iodine ion. No contributions due to moisture carryover are used in the calculational procedure, but the normal operating value of 0.1% carryover is implied. Note that the partition coefficient for iodine is the equivalent of 1% carryover and, hence, that iodine volatility is the dominant assumed release mechanism. Again, as in normal operations, no retention of noble gases is implied.

587

For Westinghouse plants, the use of the calculational procedure may be illustrated by the analysis given in the Final Safety Analysis Report for the Alvin W. Vogtle plant (26). For this plant the LOFTRAN code was used to analyze the mass and energy balance over the first 30 minutes and to provide conservative estimates of the SGTR break flows and quantities of steam released to the atmosphere. In the sequence analyzed, the SGTR (at 0 sec) causes a loss of primary pressure and inventory leading to reactor trip after about 285 seconds. The reactor trip automatically trips the turbines. If offsite power is unavailable, the steam dump valves do not open and steam generator pressure increases rapidly, the safety relief valves open and steam is discharged directly to the atmosphere. During the initial 30 minutes of the fault the operator is assumed to throttle the auxiliary feedwater flows to control steam generator level, to identify the faulted steam generator and to isolate it by halting auxiliary feedwater flow and by equalizing primary and faulted steam generator pressure at a value below the safety relief valve settings. Steam discharge will continue from the intact steam generators via the power-operated relief valves, to remove decay heat from the reactor core and to reduce primary circuit temperature. Compared with the MB-2 tests, the opening of the safety relief valve after about 300 seconds is directly comparable with the event seen in the full SGTR/SORV transient (Test 12) and with those studied in the overfill tests (Tests 10 and 11), and may be expected to give a transient release. The remainder of the steam discharge, from 300 to 1800 seconds, is essentially identical with the steady-state tests carried out on MB-2 and may be expected to give steady-state releases.

Using the LOFTRAN code, the Vogtle FSAR analysis predicts that 104,400 lbm of primary coolant will enter the faulted steam generator over the 30 minute period. For the first 300 seconds, before reactor trip, the flashing fraction based on primary and secondary pressures and temperatures is estimated to be 16.5%. Following reactor trip, the flashing fraction averages about 4% (5%, 300 to 120 seconds; 3%, 1200 to 1800 seconds). As about 85,000 lbm of primary coolant enters via the SGTR after reactor trip, and no credit for scrubbing is claimed, the release to the atmosphere is about 3400 lbm. (Note that this is a significant reduction from the release assumed in earlier analyses (27), where a constant 17% flashing fraction was assumed). For iodine partition in

588

the condenser before reactor trip and in the bulk steam generator water after reactor trip, the recommended coefficient of 100 was used (partition factor of 0.01).

If the Vogtle FSAR analysis is compared with the present MB-2 test data, it is clear that the present data will have no impact on the quantity of iodine released from the condensers or from the bulk steam generator water, as this is determined solely by volatility. The data do show, however, that no additional contribution due to moisture carryover need be considered. However, should iodine volatility be shown to be much less, then the lower carryover levels predicted by the MB-2 results would significantly reduce the quantity released as compared with the current implied carryover level of 0.1%. For activity release due to flashing primary coolant, the MB-2 test data show that the assumptions made in the current calculational procedure overestimate the quantity released. For the Vogtle FSAR analysis, and using the present MB-2 data, the quantity of primary coolant released would consist of two components, namely a transient release as the safety relief valves open, followed by a steady-state release over the period 300 to 1800 seconds. For the initial transient release, the MB-2 data predict the equivalent of 100% primary coolant bypassing for 0.4 seconds. At the Vogtle SGTR break flow rate of about 65 lbm/sec this corresponds to a release of 26 lbm. Over the remaining 15,000 seconds until isolation, the MB-2 steady-state value of 0.001% primary coolant bypassing would predict an additional release of 0.85 lbm from 85,000 lbm primary coolant. Thus the MB-2 data predict a release dominated by the initial transient release and about two orders of magnitude less than that predicted by the current calculational procedure. While this estimate is based on results obtained at normal water level, a similar release would be predicted if the break becomes exposed provided that transient releases do not occur at lower water levels.

From this comparison, the present MB-2 data indicate that the current calculational procedure substantially overestimates the fraction of primary coolant released due to primary coolant bypassing. From this it follows that even if scaling factors to account for differences between MB-2 and full size units are used, a significant reduction in the overall activity release would result if the present MB-2 data were used to calculate the releases due to primary coolant bypassing in SGTR faults. The implications which stem from these findings are outside the scope of this report, but should be considered when the current calculational procedure for SGTR radiological consequence analysis is revised.

8-3. CONCLUSIONS

The main conclusion from the MB-2 data is that there is very little primary coolant bypassing or any increase in moisture carryover under steady state SGTR/SORV fault conditions. From this it follows that the release of radioactive fission products by entrainment may not be a significant factor under steady-state conditions, leaving, for iodine, volatility as the only mechnism for activity release. In contrast to the steady-state behavior, short-term perturbations gave releases which were the equivalent of the steady-state releases for ten or tens of hours. Of these transients, the largest occurred when the safety relief valve was opened and were primarily due to bypassing or carryover, depending on water level. The data suggest that such transients could be important factors in the overall release and that they must be considered in any model or computer code for calculating activity release.

Under steady-state conditions and at normal water levels the measured carryover at 100% power was 0.001 to 0.002%. At 2 to 10% power (i.e., at SORV flow rates), under the conditions of the initial phases of the fault at normal secondary temperatures and pressures, carryover was of the order of 0.0005%, a factor of three lower. At later stages in the fault carryover could not detected (< 0.0005%).

When recirculation was maintained in the model boiler, carryover at both 10% and 100% power was not affected by variations in water level. Nor was it affected when the secondary dryer was bypassed. However, flooding the dryer at 100% power gave a large increase in carryover to 10 to 20%.

At these very low carryover levels, it is concluded that the release must be due to very fine drops which are not separated out in the dryer. A bubble bursting mechanism can be shown to be consistent with the level of carryover and with the relative insensitivity to water level and power output.

In all tests, there was little evidence for significant steady-state levels of primary coolant bypassing (the direct release of some primary coolant before mixing with the bulk liquid). Very low levels of bypassing were only seen in two or, possibly, three tests at lower secondary temperatures and pressures. Again, this was of the order of 0.0007 to 0.0012%. The mechanism for the flashing of jets from orifices predicts that significant quantities of fine drops should be produced. The absence of primary coolant bypassing is, therefore, surprising and shows that efficient processes for agglomeration or removal exist in the model boiler. These findings do not support the postulates made by Postma, et al. (28, 29) and by Raghuram, et al. (30) and indicate the need for further work on the modeling of this type of process.

When recirculation was maintained, perturbations to test conditions caused transient releases. These could be produced by sudden increases in steam flow rate (as when a safety relief valve opens), the initiation of the SGTR break flow or rapid changes in level. The greatest release was caused by the swell and frothing associated with a sudden increase in steam production rate. At normal water level, with a top break SGTR, the release was mainly due to transient bypassing and, typically, was the equivalent of 100% bypassing for 0.4 seconds. At higher water level, bypassing was suppressed and carryover increased. With the dryer flooded, the maximum release was 0.4% of the total liquid mass, with no contribution from bypassing. Although small, these transient releases are the equivalent of steady-state SORV releases for the order of 10 and 100 hours respectively and, hence, could dominate the overall release during a fault.

A smaller transient was produced by the initiation of the SGTR break flow. Principally, this release was due to transient primary coolant bypassing and occurred with both top and bottom SGTR breaks. Typically, the release was equivalent to 100% bypassing for about 0.02 seconds. Rapid changes in water level also caused small transient releases of bulk water. These were of variable magnitude, but tended to be small, 0.002 to 0.09% of the total liquid mass.

When recirculation within the model boiler could not be sustained, the type of carryover behavior changed markedly. Under test conditions typical of an early stage in the SGTR/SORV fault, with the secondary side at normal temperatures and pressures, the collapse of recirculation was accompanied by a transient release of about 0.4 to 1.3% of the liquid mass, and was followed by enhanced steady-state carryover, typically 0.003 to 0.008%. The latter was an order of magnitude higher than that seen before recirculation ceased. Under less vigorous conditions, either simply lower available heat flux (hot standby type conditions) or those applicable to an intermediate stage in an SGTR/SORV fault, no transient release was seen and carryover was not significantly higher than that seen generally in these tests.

An analysis of the thermal-hydraulic data showed good agreement between predicted and measured water level for the collapse of recirculation and predicted the existence of a recognizable steam/water interface and a splash region. The latter, coupled with the bubble bursting mechanism for producing fine drops from the draining films on tube surfaces, is proposed as the source of the enhanced carryover and for the variation in carryover with thermal-hydraulic conditions. In addition, the bubble bursting mechanism can satisfactorily account for the instance of a transient release, provided that a critical heat flux exists to activate nucleate boiling in the draining films as recirculation collapses.

Once recirculation had ceased, the occurrence of transient releases was shown to be dependent on whether salts were being actively transferred onto the dry surfaces in the tube bundle. Under the thermal-hydraulic conditions found in early stages in SGTR/SORV faults, this form of hideout apparently occurred readily. Initiating the SGTR flow or raising the water level, rewetted these surfaces and caused large transient releases of up to 8% of the total available tracer mass. Under these conditions a top break SGTR gave a large transient release, but not a bottom break due to lack of access to the dry deposits. Under no conditions were significant levels of bypassing detected. Under less vigorous conditions, as at an intermediate stage in the transient, hideout of this type did not take place and no large transient releases were detected.

At low level, transient releases similar to those at normal water level were also seen. One example was produced by a sudden increase in steam flow rate and one on initiating the SGTR break flow. Both gave much greater releases, mainly due to transient primary coolant bypassing, than seen at normal water level by of about 100 and 30 times, respectively.

Although the MB-2 model boiler is a prototypical thermal-hydraulic model of a Westinghouse Model F steam generator, exact prototypical behavior in terms of moisture carryover is not expected in view of the design differences in the primary separator, the effect of differences in flow distribution in full sized units and factors such as reentrainment. A comparison of the current MB-2 results with those obtained on Model F steam generators in the steady state shows that the plant results are generally ten times higher than those seen here. Probably this is due to existence of additional mechanisms for producing fine drops in full sized units. In view of these differences, it is concluded that MB-2 is not prototypical at full power and that the plant value of 0.015% should be used at 100% power for Model F steam generators.

At 10% power the present MB-2 data show a reduction in carryover by about a factor of 3 from that at 100% power. More importantly, the data show very little evidence for primary coolant bypassing and that no increase in moisture carryover occurs under SGTR/SORV fault conditions. Since it is unlikely that bypassing will differ substantially in full-sized units, it is suggested that the MB-2 value of about 0.001% should be used to assess bypassing in SGTR/SORV faults, but it is recognized that further work is required to address the question of scaling these data.

Since moisture carryover did not increase during SGTR/SORV fault conditions, the MB-2 results show that low-power plant data may be used to assess moisture carryover for these types of fault. Although the MB-2 model boiler may become more prototypical at low power, here, in the absence of further work to demonstrate what scaling factors need be applied to the present results, it is suggested that the MB-2 values should be increased by a factor of ten, to 0.005%, for use in SGTR/SORV faults. This value is not inconsistent with the limited plant data available and, in effect, is in line with the factor of three reduction on changing from 100% to 10% power in the MB-2 tests. For transient releases under recirculating conditions, no basis for deriving a scaling factor to apply to the MB-2 data could be deduced and no recommendation can be made. The data do show, however, that transient releases could be important factors in determining the overall release during SGTR faults and that this aspect must be addressed with specific reference to the detailed steam generator and separation equipment designs in any model or computer code for calculating activity release.

At very low water level, when recirculation had collapsed, large transient releases and increased carryover occurred under conditions typical of an early stage in an SGTR/SORV fault, but not under intermediate stage SGTR/SORV conditions (i.e., at lower pressures and temperatures, as in Test 14). At present, the magnitude of similar effects in full-sized steam generators cannot be assessed, but it is clear from the data that an equally important factor in determining releases will be the thermal-hydraulic conditions that will exist at the time when recirculation fails and the tube bundle begins to dry out. Thus, in SGTR/SORV faults with a fully isolated steam generator, where dryout will occur at a later stage in the fault, large transient releases are unlikely. However, if dryout occurs more rapidly, say in an SGTR/SLB fault, then substantial transient releases could occur. These aspects will require further assessment for each specific fault sequence, as will the consideration of any additional release due to iodine volatility under conditions where primary coolant may evaporate to dryness on the dry tube surfaces. The latter consideration could suggest that maintaining recirculation would limit the overall release in these faults, even if this is not indicated by droplet carryover data alone.

Using the MB-2 results to assess activity release in the typical SGTR fault sequence employed for Westinghouse PWRs, it is found that the predicted quantity of primary coolant lost directly to the atmosphere is two orders of magnitude less using the MB-2 data than is predicted using the current calculational procedure for this fault. Furthermore, the release is dominated by the transient caused on opening the safety relief valve, with little steady-state contribution. Although some scaling may be required for use in full-sized units, the MB-2 data show that the current procedure substantially overestimates activity release due to flashing primary coolant and that a significant reduction in overall activity release would result if the MB-2 data were used. It is recommended that these data should be considered when the current calculational procedure is next revised.

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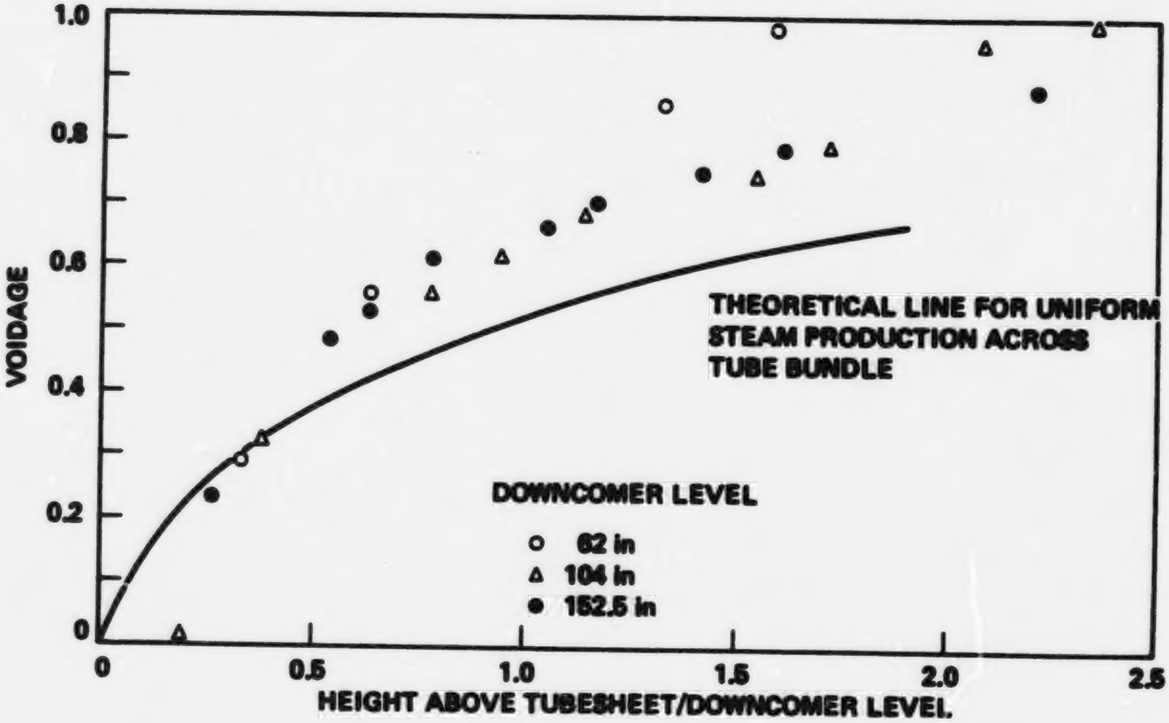

Figure 8-1. Measured and Predicted Voidage with Respect to Height in Model Boiler

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597

Appendix A

TEST REPORT: MB-2 AEROSOL ATTENUATION TEST

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598

ABSTRACT

An experiment has been conducted to measure the aerosol attenuation by the secondary side structures of the Model Boiler No. 2 (MB-2), a power-scaled model of the Westinghouse Model F PWR steam generator. The tests were conducted at ambient temperature and pressure using water droplets of either 2.1 um or 53 um aerodynamic mass median diameter (AMMD). These aerosols were introduced either at the top of the U-tubes or at the bottom of the tube bundle through injector tubes which simulated a tube rupture. The aerosols were sampled by millipore filters and cascade impactors at both the inlet to the injector and at the outlet of a stuck open relief valve located at the top center of the MB-2 shell. For an equivalent tube bundle velocity of 2 ft/s (representing a single tube rupture), the 53 um droplets were attenuated by a factor of 11, and the 2.1 um droplets were attenuated by a factor of 3.3 . This attenuation does not include any effects due to temperature and pressure, such as steam condensation on the walls of the secondary heat transfer system (Stephan flow), or onto the aerosols.

INTRODUCTION

Experience with PWR steam generators has shown that, under normal operating conditions, a small number of the tubes are prone to leak due to corrosion and mechanically induced damage. As a result, some 300 small leaks and six tube rupture incidents have occured in PWR steam generators in the United States(1). In the tube rupture incidents, minute amounts of radioactive primary coolant was released to the atmosphere via the secondary coolant safety relief valve. The amount of radioactivity released in these tube rupture incidents was small due to the limited amount of radioactivity in the primary coolant water and retention and scrubbing in the steam generator. However, it is possible that in TMLB' accidents(*) in which the core meltdown is accompanied by dried-out steam generators, the high pressure primary side steam could cause a steam generator tube rupture and vent to the secondary side, open the safety relief valve, and release large amounts of radioactivity directly to the atmosphere.

In order to study this problem , Westinghouse Electric Company, (W), the Electric Power Research Institute, EPRI, the United States Nuclear Regulatory Commission, NRC, and the U. K. Central Electricity Generating Board, CEGB, have sponsored a cooperative experiment to investigate the attenuation of aerosols by the structures within a model of a PWR steam generator: the Model Boiler No. 2 (MB-2) located at the Westinghouse Engineering Test Facility in Tampa, Florida.

(*) TMLB'is a PWR core-melt accident sequence which is initiated by the loss of all AC power and the loss of reactor coolant system heat removal(2). PWRs are designed so that if both offsite power is lost and the emergency diesel generators fail to operate, decay heat can be removed from the reactor coolant by the steam generators fed by steam driven feedwater pumps. If this mode of heat removal fails to operate, the reactor coolant water will eventually boil away through the pressure relief valves. The core will then melt and release radioactive fission products into the high pressure steam on the reactor side of the dried-out steam generator.

MODEL BOILER DESCRIPTION[3]

The Model Boiler No. 2 (MB-2) is an approximately 1 percent power-scaled model of the Westinghouse Model F steam generator, a feedring type unit. Designed to be geometrically and thermo-hydraulically similar to the Model F in the important areas, the MB-2 is capable of generating 10 Mwt of power. A schematic of the model is shown in figures 1-a and 1-b.

TUBE BUNDLE

The MB-2 tube bundle is composed of 52 tubes arranged in a rectangular array having 13 tube rows and 4 tube columns, as shown in figure 1b. All tubes have an outside diameter of 1.75 cm (11/16 in.) and a 1 mm (0.040 in.) wall thickness, which is the same as the tubes in the model F steam generator, and are configured to the same 2.49 cm (0.98 in.) square-pitch array. As a result, primary and secondary unit flow areas for the model and the full-size steam generator are identical. The straight length of the tube bundle is 6.69 m (21.94 ft.), which is about 0.5 m (20 in.) shorter than the model F. The U-tubes fit into a rectangular cross-section wrapper box with a rectangular to circular transition cone at the upper end (see figures 1-a). The circular flange on the transition cone mated with a similar flange on the 17.8 cm (7 in.) diameter riser leading to the modular primary separator in the upper shell region.

No modelling of the formation of droplets from the rupture of a MB-2 tube has been performed. However, Wu and Chuang[4] considered a steam generator with a bundle of 1.91 cm (0.75 in.) diameter tubes on a 2.54 cm (1 in.) triangular pitch. They modeled the collection of droplets from a ruptured tube as an inertial impaction process, since some of the droplets hit and coalesce on adjacent tube walls during discharge from the ruptured tube. Droplet removal by tubes in rows beyond the first was not considered in this analysis. At the lowest pressure-drop considered, 1.034 MPa (150 psi), removal efficiency became significant for droplets > 4 μm diameter, reaching 60% for 22 μm diameter droplets. Larger droplets, or higher gas velocity result in higher removal efficiency.

MODULAR PRIMARY SEPARATOR

The MB-2 modular separator is a 17.8 cm (7 in) axial cyclone consisting of four swirl vane blades oriented at 37° from the horizontal, the same as specified in some existing Westinghouse designs. Geometry of the primary steam separator is defined by the quantities shown in figure 2. The normal function of the swirl vane is to create a centrifugal force which collects water drops from the incident two-phase fluid. The modular separator can readily remove large (>40 μm) drops, but is not efficient in removing the micrometer size droplets. Young, et al.(3) have applied Stokes' law to find key parameters for drop collection efficiency. This leads to:

$$\mathrm{Stk} = \frac{d^2 \gamma \rho_f u_{fo} \cos\beta}{9 \mu_g (R_r^2 - R_1^2) / R_1} \qquad (1)$$

Where: R_r = riser inner radius

R_1 = hub radius

d = drop diameter

β = angle of blade to horizontal

γ = angle of blade span

u_{fo} = liquid phase velocity

$u_{f\theta}$ = liquid phase circumferential vel.

u_{fr} = liqiid phase radial velocity

μ_g = steam viscosity

Stk = Stokes Number

The larger the Stokes number (Stk), the more efficient is the swirl vane, since:

$$r^2 - R_i^2 = Stk\ (R_r^2 - R_i^2) \qquad (2)$$

However, Beeckmans(5) has recently found that cyclone efficiency cannot be correlated in terms of the Stokes number alone and that the Reynolds number (Re) must be included in the correlation. He used the correlation that efficiency varies with:

$$(Re)^b \cdot (Stk)^{0.5} \qquad \text{where: b is an empirical constant.} \qquad (3)$$

Parker, et al.(6) have sucessfully used Beeckmans' correlation (with b=1) to correlate high-temperature and high-pressure cyclone dust collector data on the same curve as room- temperature and low-pressure data (see figure 3). They used a 5 cm (2 in.) diameter, rectangular-inlet, tangential-entry, reverse-flow cyclone operated at 2.5 m/s. They found that the correlation of the 50% cut diameter against the product of $(Re) \times (Stk)^{0.5}$ accounted for the observed temperature and pressure effects in their tests as well as those(7) from a 15 cm (5.9 in.) diameter cyclone operated at 36 m/s. Minimum efficiency for 3 µm particles doubled as the pressure was increased from 157 kPa (3 atm) to 1,311 kPa (25 atm). However, minimum efficiency decreased from 18% to 5% as the temperature was increased from 22 °C to 693°C .

Parker, et al. noted that: (a) although the efficiency clearly increased with increasing gas pressure, none of the current theories indicated this effect; (b) the effects of high-temperature and high-pressure tend to cancel each other out, and therefore the effect is more likely to be related to density than to temperature or pressure alone; (c) the curves of efficiency against particle aerodynamic diameter all showed a minimum efficiency for particle diameters between 2 and 4 μm; (d) apparently, the Reynolds number, and hence the flow pattern in the cyclone, is very important in determining particle deposition.

Wu and Chuang(4) have calculated from velocity profile data(8) the removal efficiency of a 10.16 cm (4 in) diameter swirl vane cyclone steam separator (See Figure 4). For 0.9 m/s (3 ft/s) steam velocity at the inlet of the separator, it is nearly 100% efficient for 80 μm diameter drops, but only 50% efficient for 35 μm diameter drops and 25% efficient for 23 μm diameter drops. It will not remove drops smaller than 10 μm diameter. (3.5 ft/s gas velocity in the MB-2 separator is equivalent to 2 ft/s in the MB-2 tube bundle.)

SECONDARY SEPARATOR (Steam Dryer)

The gas flows from the modular steam separator upward through a 1.268 ft^2 duct to the secondary separator, which consists of a perforated plate followed by spaced corregated (chevron) dryer vanes (see figure 5). Under normal operating conditions, the efficiency for steam separation can be formulated(3) in terms of the Stokes number (Stk) and the blockage parameter H (= h/y_o). In effect, a fractional separation efficiency is defined by:

$$\eta_P = \frac{2}{H} \quad \frac{1}{(1 + Stk^2)^{0.5}} \qquad (4)$$

for a unit cycle (P) of chevron plates.

The overall efficiency is written as:

$$\eta = 1 - (1 - \eta_P)^{aN} \qquad (5)$$

for the number (N) of wave cycles (P) and the empirical factor (a = 0.5 ~ 0.6).

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A similar expression was previously developed by Chuang, et al.(9) using a semi-empirical approach. They obtained details of the gas velocity profiles in the chevron passages by observing the streamlines in a plexiglass model and combined this data with droplet trajectories calculated from the equation-of-motion in order to obtain the removal efficiency. Their results compare favorably with experimental data for solid aerosols(10) (See Figure 6). They combined the the inertial, diffusion, interception and sedimentation removal efficiencies and plotted the total removal efficiency as a function of drop diameter with steam velocity as a parameter (See Figure 7). Interpolation from their plots(4) shows that droplets of 0.8 μm have the maximum probility of penetrating the steam dryer at a steam velocity of 0.22 m/s (0.73 ft/s). (note: 0.73 ft/s in the dryer is equivalent to 2 ft/s in the MB-2 tube bundle.) The efficiency was : 1% for 2 μm diameter drops; 10% for 6 μm diameter drops; 50% for 15 μm diameter drops; 80% for 30 μm drops; and 100% for 40 μm drops.

MB-2 AEROSOL TEST

The MB-2 was configured with two simulated break elements (injector tubes extending through the shell of the MB-2 and through the wall of the wrapper box into the center of the tube bundle) into which water droplet aerosols could be injected. The break elements were located at the top of the U-bends (elevation= 282 in. from the tubesheet) and at the bottom of the U-tubes (elevation= 6 in. from the tubesheet) (see figure 8). Nitrogen sweep gas (up to 4000 ft^3/hr) was admitted via the MB-2 blowdown pipe (elevation= 0.5 in. from the tubesheet). The MB-2 was maintained at ambient temperature and pressure during the test.

The aerosols were produced by injecting water and nitrogen into a Spraying Systems Model 1/4-J nozzle with a No. 140-6-52-70 tip. Depending on the nozzle

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connections for the gas and water, aerosols with either 53 µm or 2.1 µm aerodynamic mass median diameter (AMMD) could be produced (See Appendix). These aerosols were sprayed into the 5 ft. long by 23.5 in. diameter horizontal aerosol chamber whose outlet was connected by the original 202 in. length of 3/4 in. ID tubing to one of the simulated SGTR break elements. A minimum of 5 minutes of steady state aerosol injection was allowed prior to initiation of aerosol sampling. Figure 9 is a P&I diagram of the system.

The water for the spray nozzle was doped with 100 ppm of LiOH in order to provide a tracer. Millipore filters and cascade impactors (see figure 10) were used to sample the aerosols at the inlet to the MB-2 SGTR break element and at the outlet of the safety relief valve at the top of the MB-2 shell. Expansion chambers were provided at both the inlet and outlet to reduce the gas velocity so that sampling could occur under approximately isokinetic conditions. The samples were obtained by pulling a known volume of gas through either a millipore filter or a cascade impactor. Ten liter vacuum flasks, fitted with Bourdon type vacuum gauges and gas restriction orifices, were used to pump the gas. At the end of each run, the filters and impactor stages were then soaked in a known volume of water for ten minutes. The resulting solutions were then analyzed using a Perkin-Elmer Model 360 atomic absorption spectrophotometer, which had been previously calibrated against lithium solution standards. The minimum detectable level of lithium was 0.2 ppb. The mass of lithium on each millipore filter and impactor stage was estimated from the lithium concentration and the volume of dilution water. Aerosol mass concentrations were calculated from the lithium masses and the known volumes of gas passing through the samplers. Three concentration and two impactor samples were obtained at both the inlet and exaust during each run. Because of the limited amount of LiOH permitted in these tests (in order to avoid potential long term corrosion of the MB-2 system), many of the impactor samples were below the 0.2 ppb limit of lithium detection. As a result, only a few of the impactors supplied useful data. However, all of the concentration samples (obtained on millipore filters) were above the minimum detectable level. Each concentration reported in Table 1 is the average of three independent measurements.

Approximate sweep gas velocities in the tube bundle were estimated from the MB-2 cross-sectional area (see figure 1b) and the nitrogen flow rate measured by the pressure drop across a venturi in the inlet to the blowdown pipe (See figure 9). These velocities were corrected for the gas pressure in the MB-2 model, and the additional gas sweeping through the aerosol generator.

Figure 11 and Table 1 present the attenuation of the aerosols as a function of the gas velocity in the tube bundle. For a given gas velocity, aerosols injected at the top of the tube bundle show the least attenuation, except for the point corresponding to the injection of 2.1 µm AMMD particles at a equivalent bundle velocity of 1.4 ft/s . There is no current explanation for this discrepancy. As expected, the 53 µm AMMD particle size distribution (see figure 13) is attenuated substantially more than the small particle distribution. The MB-2 system can be viewed as an aerosol filter with a minimum attenuation at 1 to 2 µm and a "cut diameter", the diameter of the particle which is collected at 50% efficiency, which decreases as the gas velocity increases.

It has been estimated that following a single tube rupture during a TMLB' accident, the steam/gas flow velocity in the tube bundle would be ~ 2 ft/s. At this gas velocity in the MB-2, the 53 μm AMMD particles injected at the bottom of the tube bundle would be attenuated by a factor of 11, while the 2.1 μm AMMD particles would be attenuated by a factor of 3.3 . Of course, this does not include any attenuation due to steam condensation on the walls of the secondary heat transfer system, or any effects due to system temperature and pressure(6,7).

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608

APPENDIX- Size Distribution of the Water Droplets Injected into MB-2

According to tests performed by the manufacturer(*), the Spraying Systems Model 1/4-J nozzle with a No. 140-6-52-70 tip should produce water droplets in the range of 30 µm MMD when used under the conditions of the MB-2 aerosol test. In this normal configuration a central water jet is broken up by radial nitrogen jets. Previously, Rockwell(**) had found that if the gas and water connections to the nozzle were reversed from those recommended by the manufacturer, the water formed a sheet which was broken up by a cental gas jet, and the nozzel would produce micrometer size water droplets. (In a separate test, molten sodium was pumped through the reversed connections to the fog nozzle, and frozen sodium drops were collected on fallout planchets located on the floor of an inert atmosphere chamber(***). Photomicrographs of the collected drops showed that they ranged from 0.9 µm to 3.5 µm diameter, with the average size being 2.6 µm. [For a geometric standard deviation of 2, the Hatch-Choate (****) equation transforms this settled mean diameter (d_s) to an Airborne Mass Median Diameter (AMMD) of 1.6 µm.] Impactor data taken 30 seconds after the end of the spray, showed airborne particles to be 1.6 µm AMMD. Since molten sodium has a

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(*) Private communication, letter dated 8/27/85 from J. Haruch (Spraying Systems Co., Wheaton, IL 60187) to R. P. Johnson (Aug 1985).

(**) R. P. Johnson and C. T. Nelson, "Interim Test Report for the High Temperature- Concentration Aerosol Tests Conducted in FY 1977," Rockwell International, Atomics International Div. internal Report: N707-TI-130019 (Sept 1977).

(***) C. T. Nelson and R. P. Johnson , "Subtask D - High Temperature- Concentration Aerosol Tests," in Quarterly Technical Progress Report LMFBR Safety Program, January - March 1977, Rockwell International Report: AI-ERDA-13196 (May 1977) (This Report is available from the NTIS, Springfield VA 22161).

(****) Hatch-Choate equation: $d_s = (\text{AMMD}) \exp(\ln^2 \sigma_g)$

619

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higher surface tension, but lower density and viscosity than water, the size of the sodium drops were somewhat smaller than those of water (see below).

In order to verify the size distribution of the droplets produced under the conditions of the MB-2 aerosol test, a calibration of the aerosol generator was undertaken at the Rockwell International Field Laboratory at Santa Susana, California. The aerosol chamber was connected by the original length of 3/4 inch injector tubing to a spare MB-2 injector which was inserted into the center of the narrow end of a rectangular enclosure (4 ft X 4 ft X 7 ft) whose long dimension was horizontal.

For the fine droplet nozzle configuration, the water was doped with 5,000 ppm lithium sulphate and impactor samples of the salted fog droplets were obtained using a five stage round jet impactor (see figure 10). Each impactor stage was washed with distilled water, and the liquid samples were analyzed by liquid ion chromatography (Dionex Model 21201 equipped with CS-1 column and guard and with a Spectrophysics Model 4270 Integrator). The chromatograph was calibrated over the range of 50 to 800 ppb lithium sulphate (minimum detectable level was 0.2 ppb). The percentage of the total salt mass passing through each impactor stage was plotted on logarithmic probability paper as a function of the impactor stage cut-off size to estimate the size distribution of the water droplets. From the average of eight impactor measurements the fog particle size was estimated to be 2.1 μm AMMD with a geometric standard deviation of 2.38 (see figure 12).

For the large particle nozzle configuration, the method of size measurement consisted of capturing fallout from the ejector in a shallow tray filled with liquid nitrogen and sieving the frozen water droplets with standard screens. The material captured on each screen was weighed, as well as the particles which passed through the finest (last) screen and were caught on a Whatmann filter. These weights were converted to percentage mass per screen. The cumulative mass percentage of all screens up to, and including a given screen was plotted against the sieve opening for each screen. Logarithmic probility paper was used to estimate the mass median diameter of the settled mass and geometric standard deviation (σ_g) of the distribution, under the assumption that the distribution was log-normal. The settled MMD estimated from an average of seven measurements was 53 µm, with a geometric standard deviation of 2.26 (see figure 13). Because the containment box was vented during the collection period, the settled MMD doesn't include all of the very fine particle fraction. Since the missing mass fraction would not have changed the shape of the distribution significantly, the distribution may be taken as equivalent to the airborne MMD . The weight fraction of particles with diameters less than 38 µm diameter is 33.5%, but the actual shape of the distribution below 38 µm is unknown. By extrapolating the data in figure 13 to small particle sizes, the weight fraction of particles less than 20 µm diameter is 10 %, the weight fraction of particles less than 10 µm diameter is 1.4% and the weight fraction of particles less than 3 µm is 0.01 %. However, this extrapolation is subject to large errors since there are no data points below 38 µm and the original data are only accurate to ± 20 % at best.

TABLE I

TEST No.	TOP/BOTTOM INJECTION	AEROSOL DIAMETER AMMD	GAS FLOW RATE ft./s	INLET CONCENTRATION* $\mu g/cm^3 \times 10^{-5}$	OUTLET CONCENTRATION* $\mu g/cm^3 \times 10^{-5}$	ATTENUATION FACTOR C_{in} / C_{out}
2	T	53 µm	1.35	$5.1^{+0.3}_{-0.3}$	$3.0^{+0.2}_{-0.4}$	$1.70^{+0.37}_{-0.2}$
2	T	53 µm	2.21	$8.3^{+0.4}_{-0.5}$	$1.1^{+0.0}_{-0.1}$	$7.55^{+1.15}_{-0.46}$
3	T	2.1 µm	1.36	$9.5^{+0.2}_{-0.2}$	$3.3^{+0.3}_{-0.2}$	$2.88^{+0.25}_{-0.3}$
3	T	2.1 µm	2.13	5.0^{+}_{-}	$1.65^{+0.3}_{-0.2}$	$3.03^{+0.41}_{-0.46}$
4	B	2.1 µm	1.41	$9.62^{+0.1}_{-0.1}$	$4.54^{+0.26}_{-0.19}$	$2.13^{+0.08}_{-0.15}$
4	B	2.1 µm	2.14	$8.0^{+0.16}_{-0.03}$	$2.3^{+0.06}_{-0.09}$	$3.48^{+0.21}_{-0.10}$
5	B	53 µm	1.24	$7.1^{+0.7}_{-0.5}$	$2.22^{+0.03}_{-0.02}$	$3.19^{+0.36}_{-0.26}$
5	B	53 µm	1.91	$13.0^{+2.2}_{-2.1}$	$1.19^{+0.18}_{-0.13}$	$10.9^{+3.86}_{-2.94}$
6	B	53 µm	2.23	$16.4^{+1.0}_{-0.9}$	$1.1^{+0.04}_{-0.02}$	$14.91^{+0.99}_{-0.95}$

* Each concentration is the average of three measurements.

612

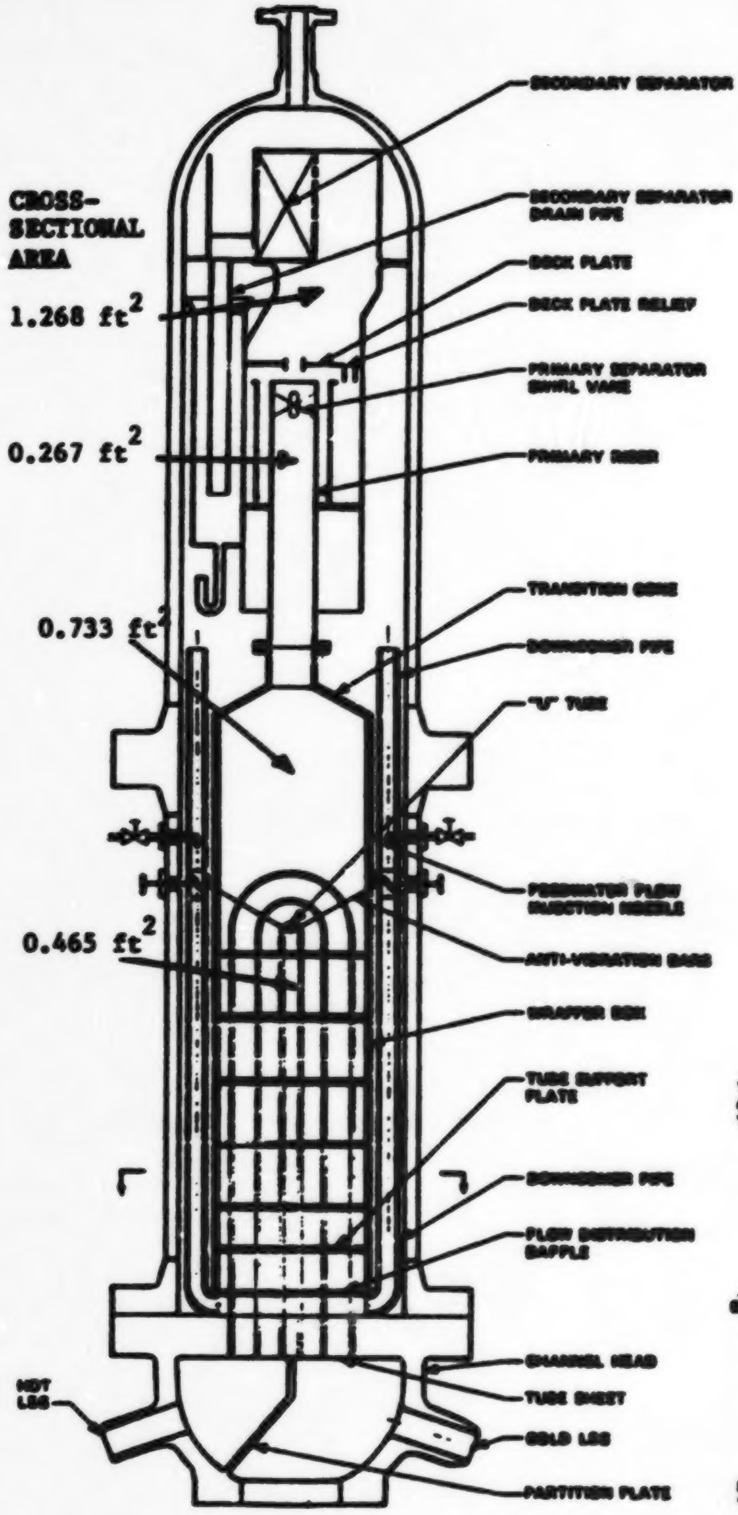
CROSS-
SECTIONAL
AREA
1.268 ft^2
0.267 ft^2
0.733 ft^2
0.465 ft^2
SECONDARY SEPARATOR
SECONDARY SEPARATOR DRAIN PIPE
DECK PLATE
DECK PLATE RELIEF
PRIMARY SEPARATOR SWIRL VANE
PRIMARY RISER
TRANSITION CONE
DOWNCOMER PIPE
"U" TUBE
FEEDWATER FLOW INJECTION NOZZLE
ANTI-VIBRATION BARS
WRAPPER BOX
TUBE SUPPORT PLATE
DOWNCOMER PIPE
FLOW DISTRIBUTION BAFFLE
CHANNEL HEAD
TUBE SHEET
HOT LEG
COLD LEG
PARTITION PLATE

Figure 1a. Model Boiler 2 Elevation

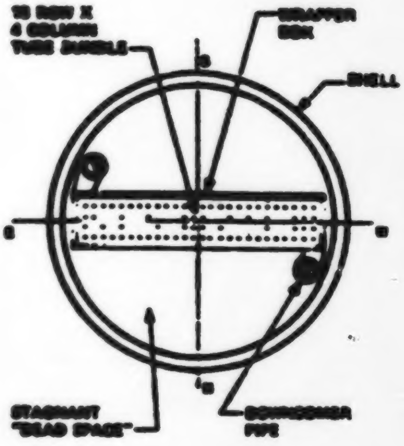
19 ROW X 4 COLUMN TUBE BUNDLE
WRAPPER BOX
SHELL
B
B
C
C
STAGNANT "DEAD SPACE"
DOWNCOMER PIPE

Figure 1b. MB-2 Cross-Section Through Tube Bundle

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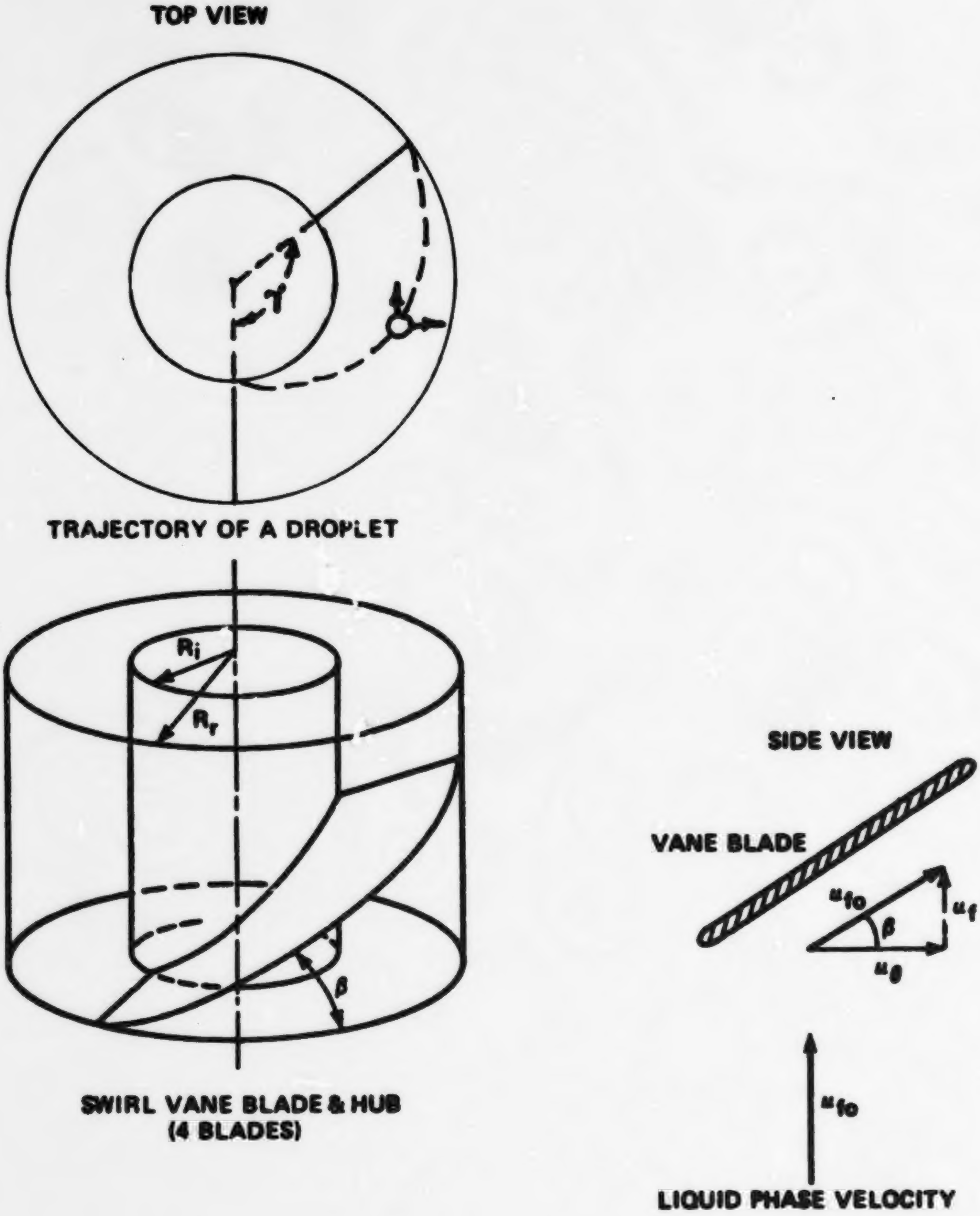
TOP VIEW
γ
TRAJECTORY OF A DROPLET
R_i
R_r
β
SWIRL VANE BLADE & HUB
(4 BLADES)
SIDE VIEW
VANE BLADE
u_fo
β
u_f
u_θ
u_fo
LIQUID PHASE VELOCITY

FIGURE 2: Swirl Vane Blade Configuration and Liquid Drop Motion

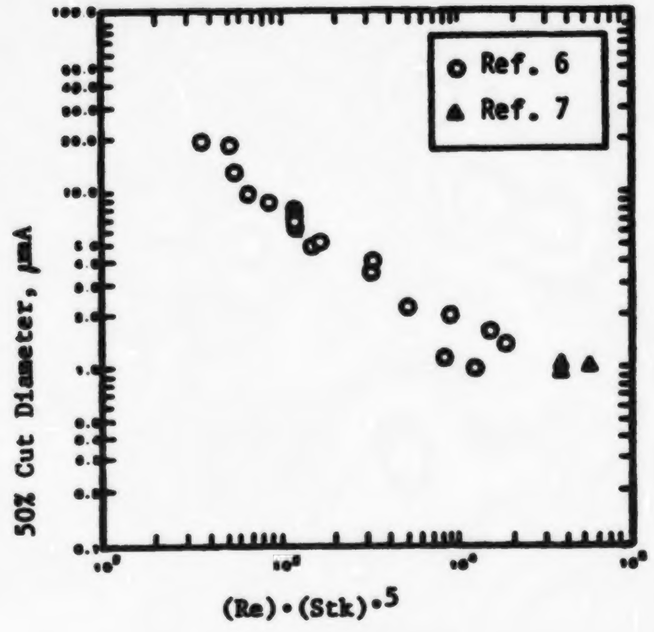

FIGURE 3: Correlation with 50% Cut Diameter (Ref. 6)

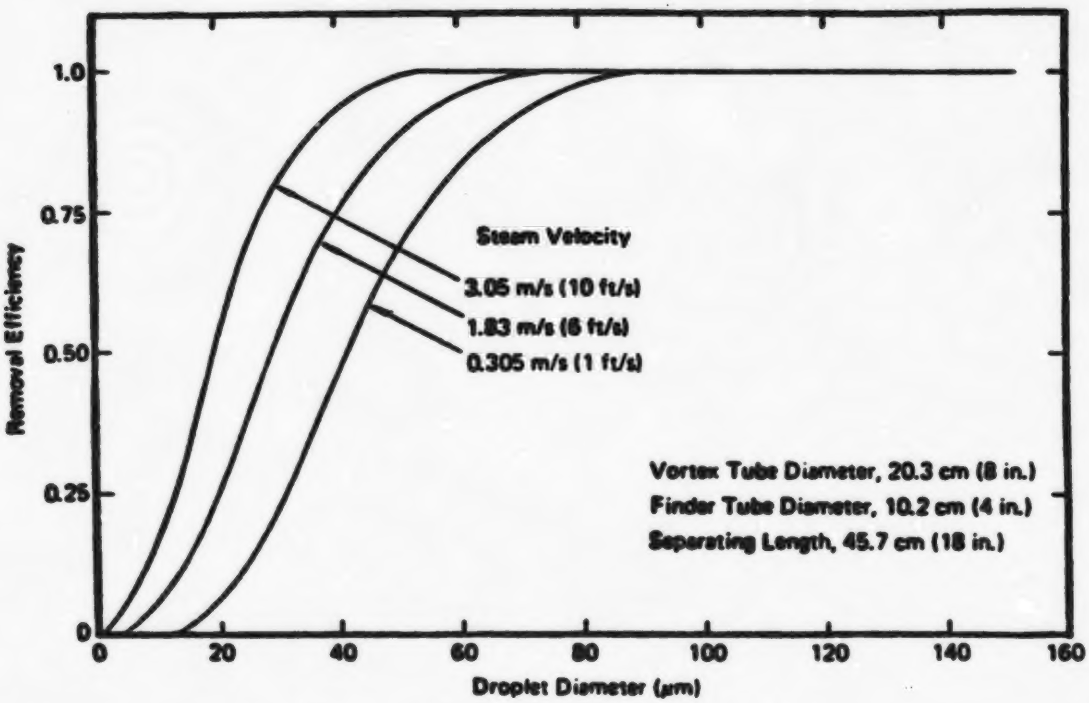

FIGURE 4: Droplet removal efficiency of an upcomer steam generator (Ref. 4)

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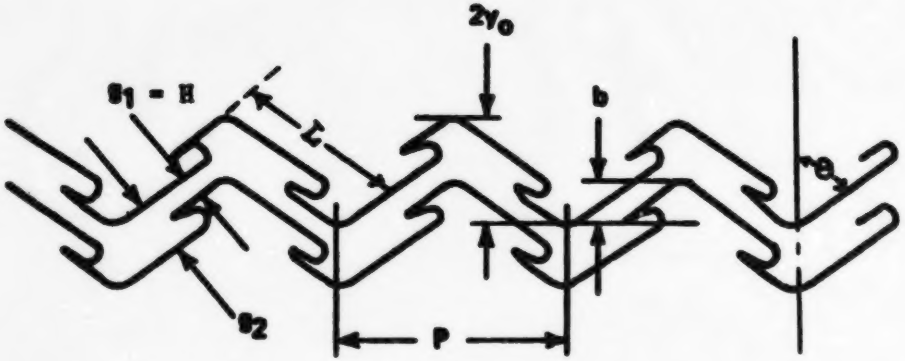

NARROW GAP	g_1 = 5.69 mm (0.224 in.)	; N=4
WIDE GAP	g_2 = 11.73 mm (0.462 in.)	; θ=60°
PERIOD	P = 51.82 mm (2.04 in.)	; L=4.146 cm
AMPLITUDE	y_0 = 11.84 mm (0.466 in.)	
BLOCKING	b = 10.16 mm (0.4 in.)	

($b = h - 2y_0$; $h = 1.332$)

FIGURE 5: Chevron plates and water drop/ steam flow path in MB-2 dryer

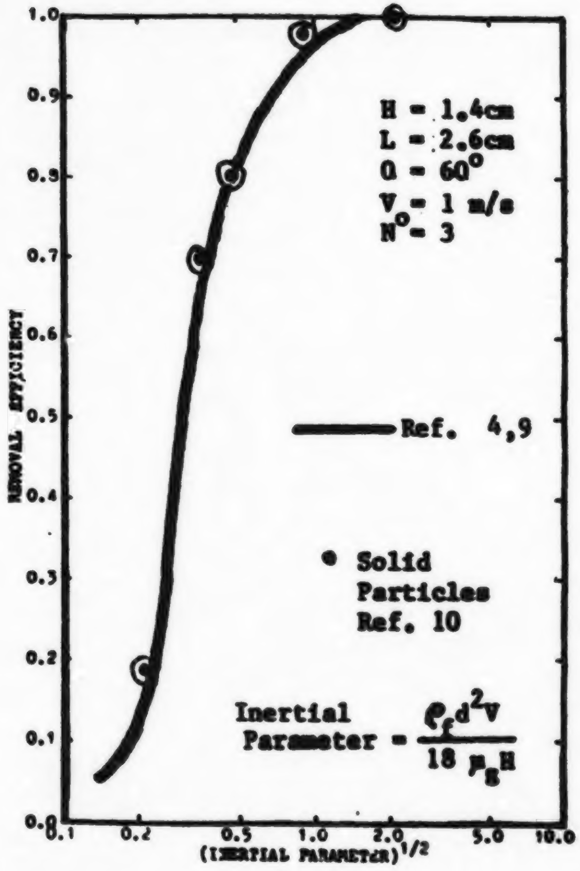

FIGURE 6: Droplet removal efficiency of Ref. 4 Steam Dryer due to inertial impaction.

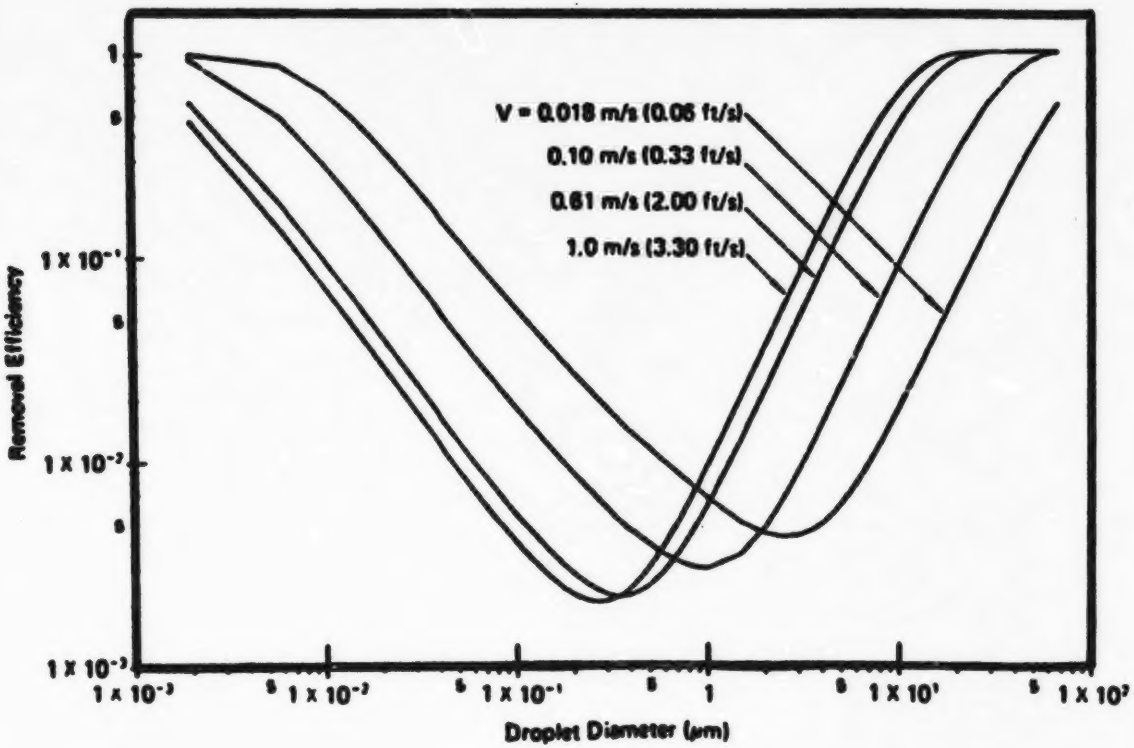

FIGURE 7: Effect of steam flow velocity in the steam dryers on the droplet removal efficiency. (Ref. 4)

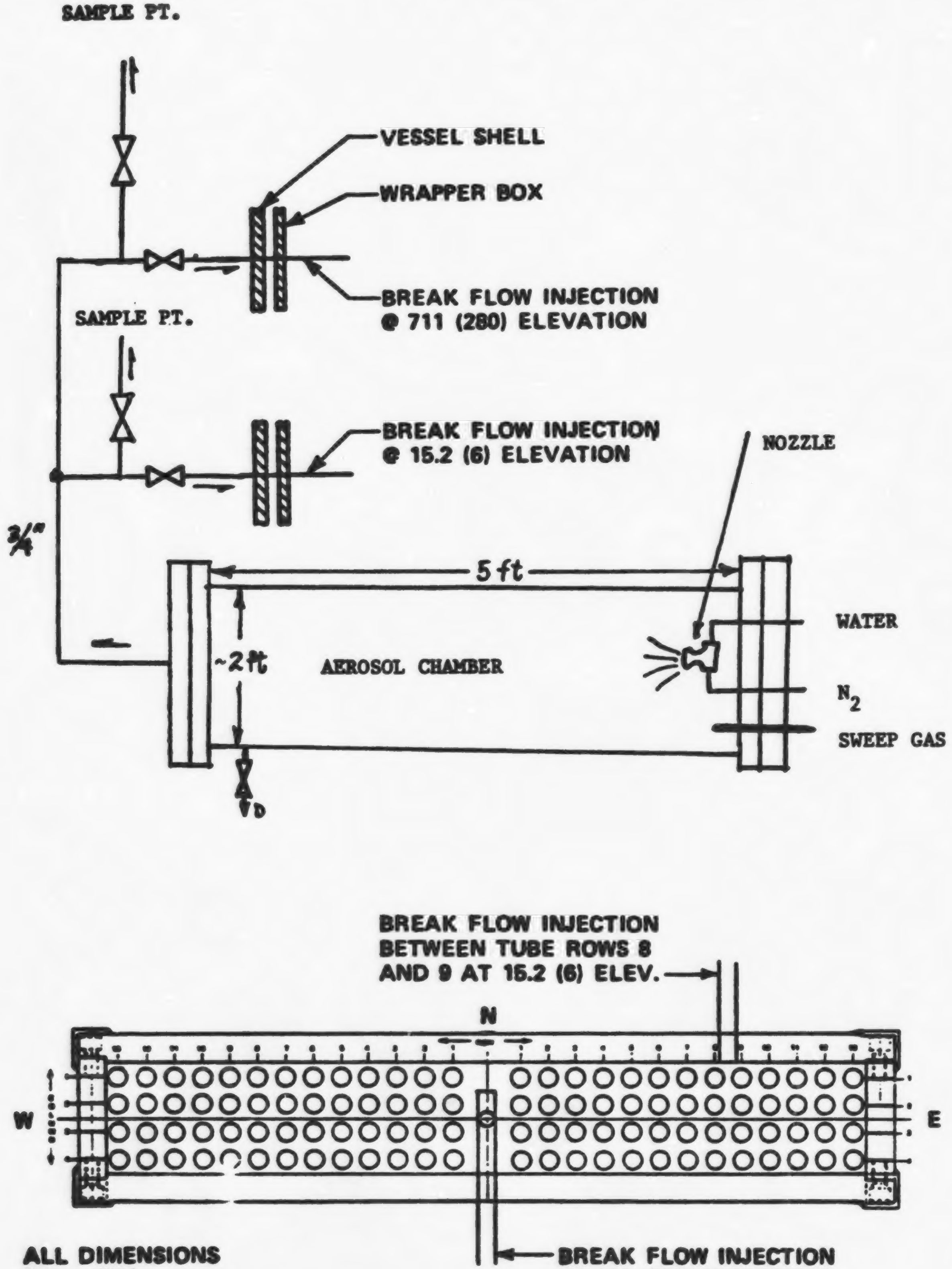
SAMPLE PT.
VESSEL SHELL
WRAPPER BOX
BREAK FLOW INJECTION @ 711 (280) ELEVATION
SAMPLE PT.
BREAK FLOW INJECTION @ 15.2 (6) ELEVATION
NOZZLE
3/4"
5 ft
~2 ft
AEROSOL CHAMBER
WATER
N_2
SWEEP GAS
D
BREAK FLOW INJECTION BETWEEN TUBE ROWS 8 AND 9 AT 15.2 (6) ELEV.
N
W
E
ALL DIMENSIONS IN cm (in.)
BREAK FLOW INJECTION AT 711 (280) ELEVATION

FIGURE 8: Loop Modifications for MB-2 Aerosol Tests

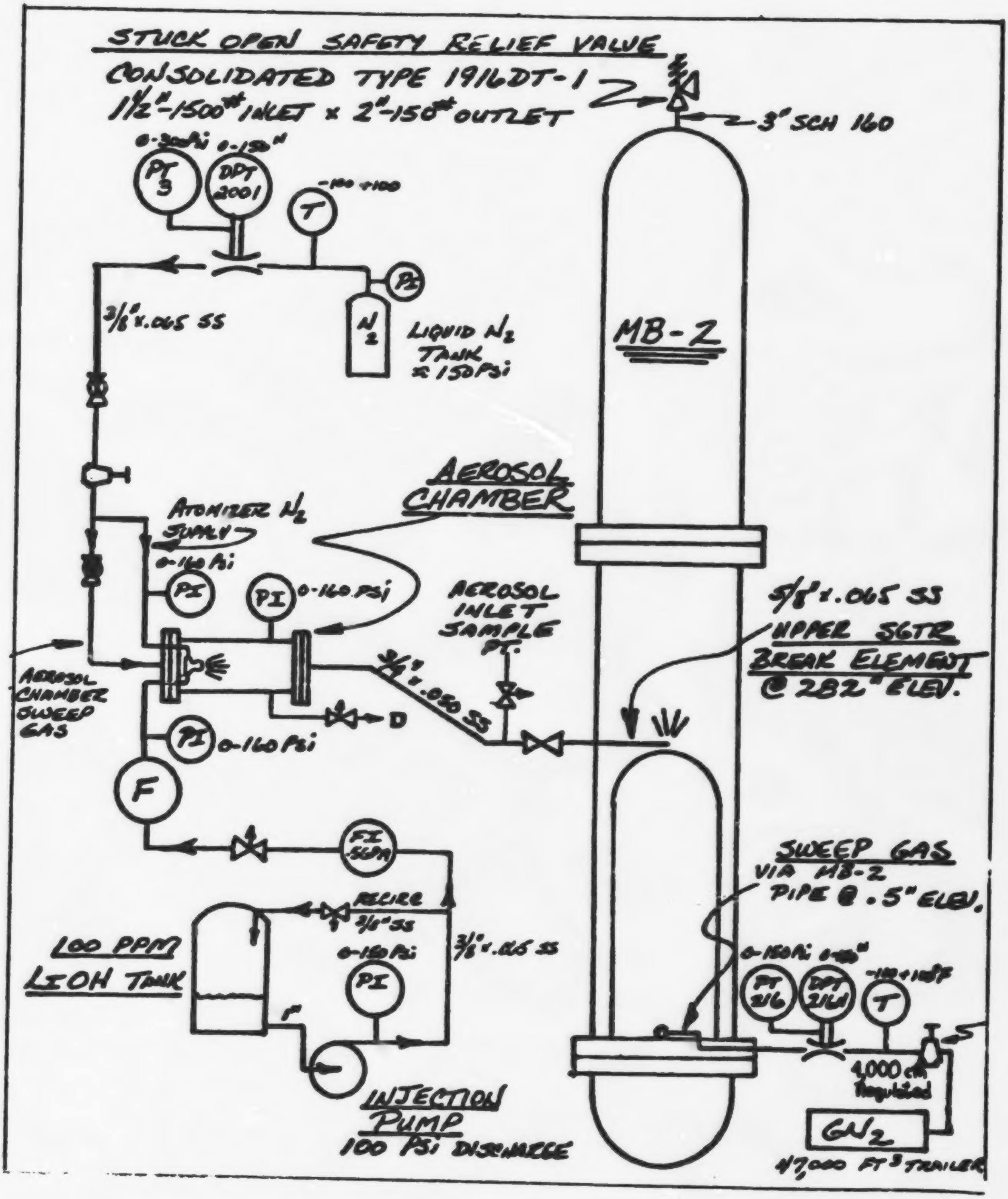
STUCK OPEN SAFETY RELIEF VALVE
CONSOLIDATED TYPE 1916DT-1
1½"-1500# INLET x 2"-150# OUTLET
3" SCH 160
0-300Psi
0-150"
PT 3
DPT 2001
T
-100 +100
PI
3/8" x.065 SS
N2
LIQUID N2 TANK ≈ 150Psi
MB-2
AEROSOL CHAMBER
ATOMIZER N2 SUPPLY
0-160 Psi
PI
PI
0-160 Psi
AEROSOL INLET SAMPLE PT.
AEROSOL CHAMBER SWEEP GAS
3/8" x.050 SS
D
PI
0-160 Psi
F
FI SGPM
RECIRC 3/8" SS
3/8" x.065 SS
100 PPM LIOH TANK
0-160 Psi
PI
INJECTION PUMP
100 PSI DISCHARGE
5/8" x.065 SS
UPPER SGTR BREAK ELEMENT @ 282" ELEV.
SWEEP GAS VIA MB-2 PIPE @ .5" ELEV.
0-150Psi
0-150"
PT 216
DPT 2161
T
-100 +100°F
4,000 cfh Regulated
GN2
47,000 FT3 TRAILER

FIGURE 9: P & I Diagram of MB-2 Aerosol Test

STAGE	CUTOFF DIA (µm)	HOLE SIZE (cm)
0		0.114
1	7.0	0.094
2	4.8	0.057
3	2.4	0.034
4	1.1	0.019
5	0.45	0.094

Impactor Size: 3 cm dia X 3.5 cm long

Inter-stage spacing: 0.2 cm

20 Holes each stage

Flow Rate ≅ 1.4 l/min

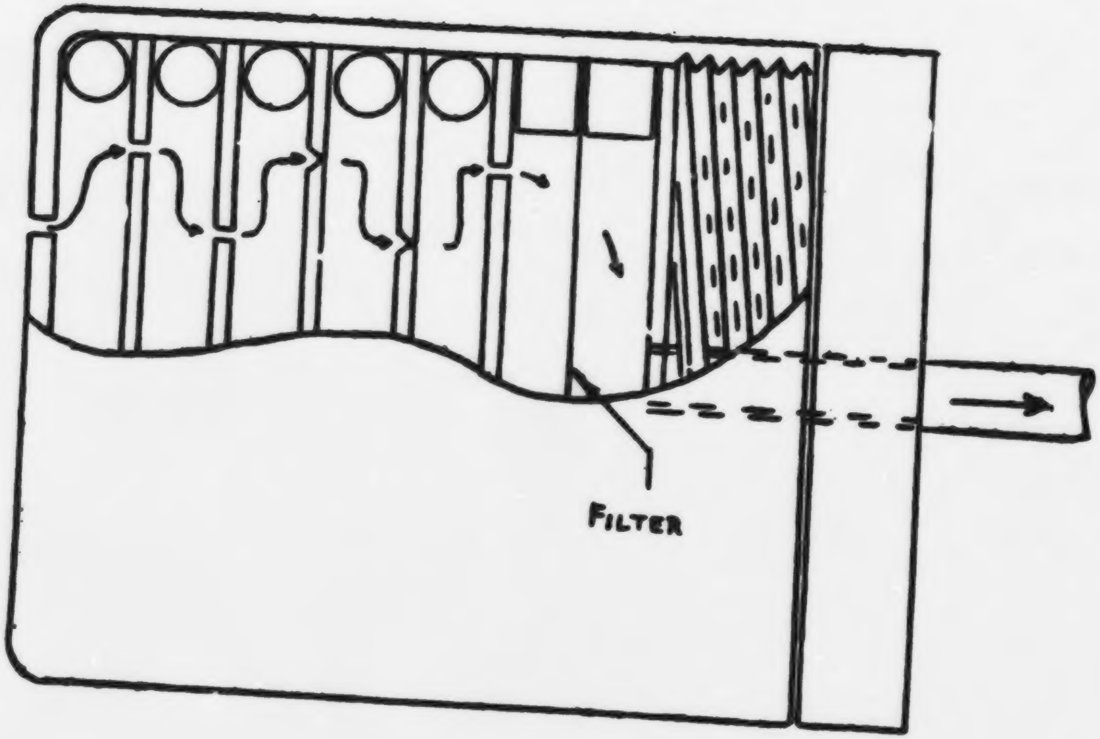

FIGURE 10: 5-Stage Impactor

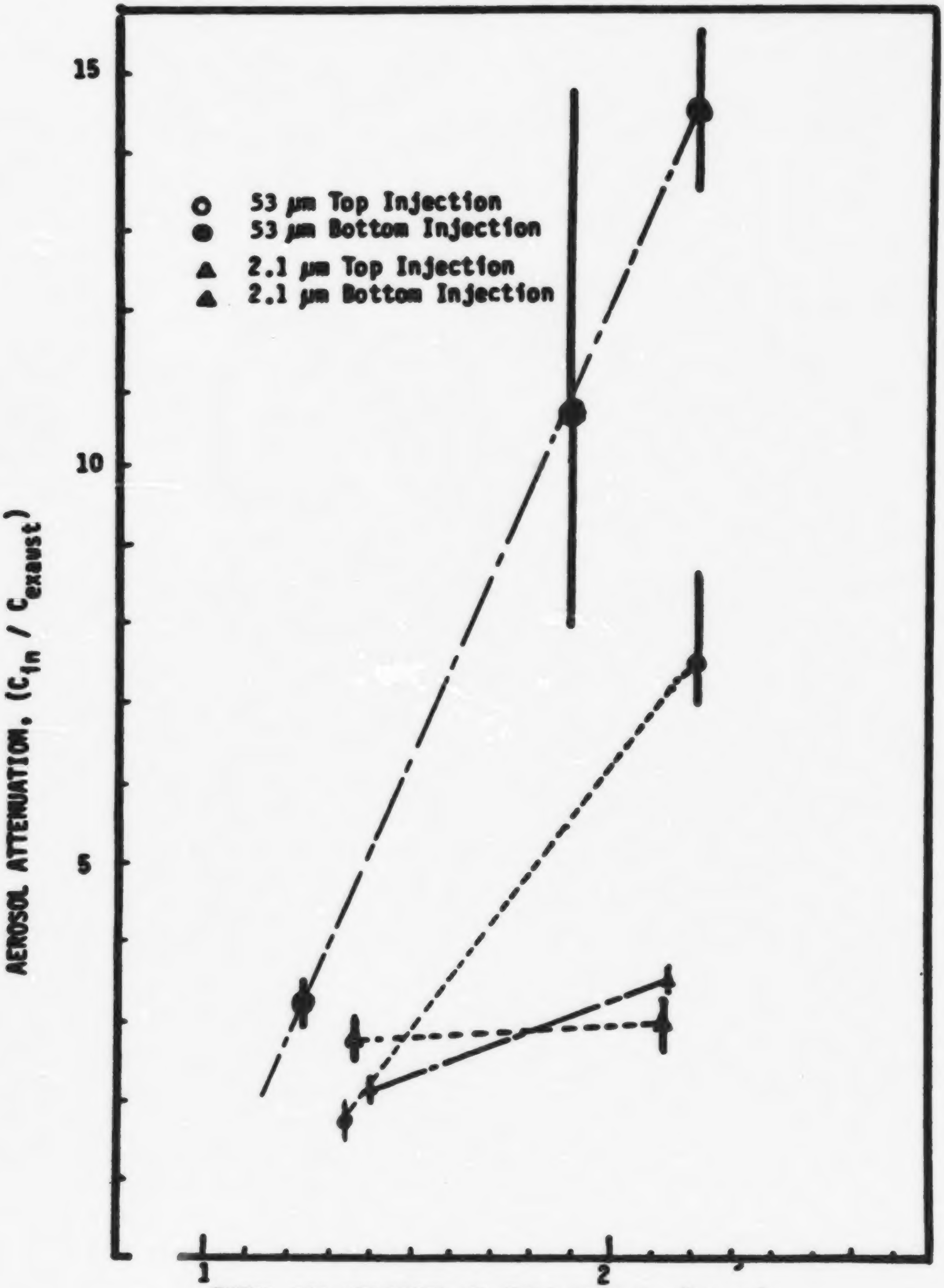

FIGURE 11: Aerosol Attenuation vs Total Gas Velocity in MB-2 Tube Bundle

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621

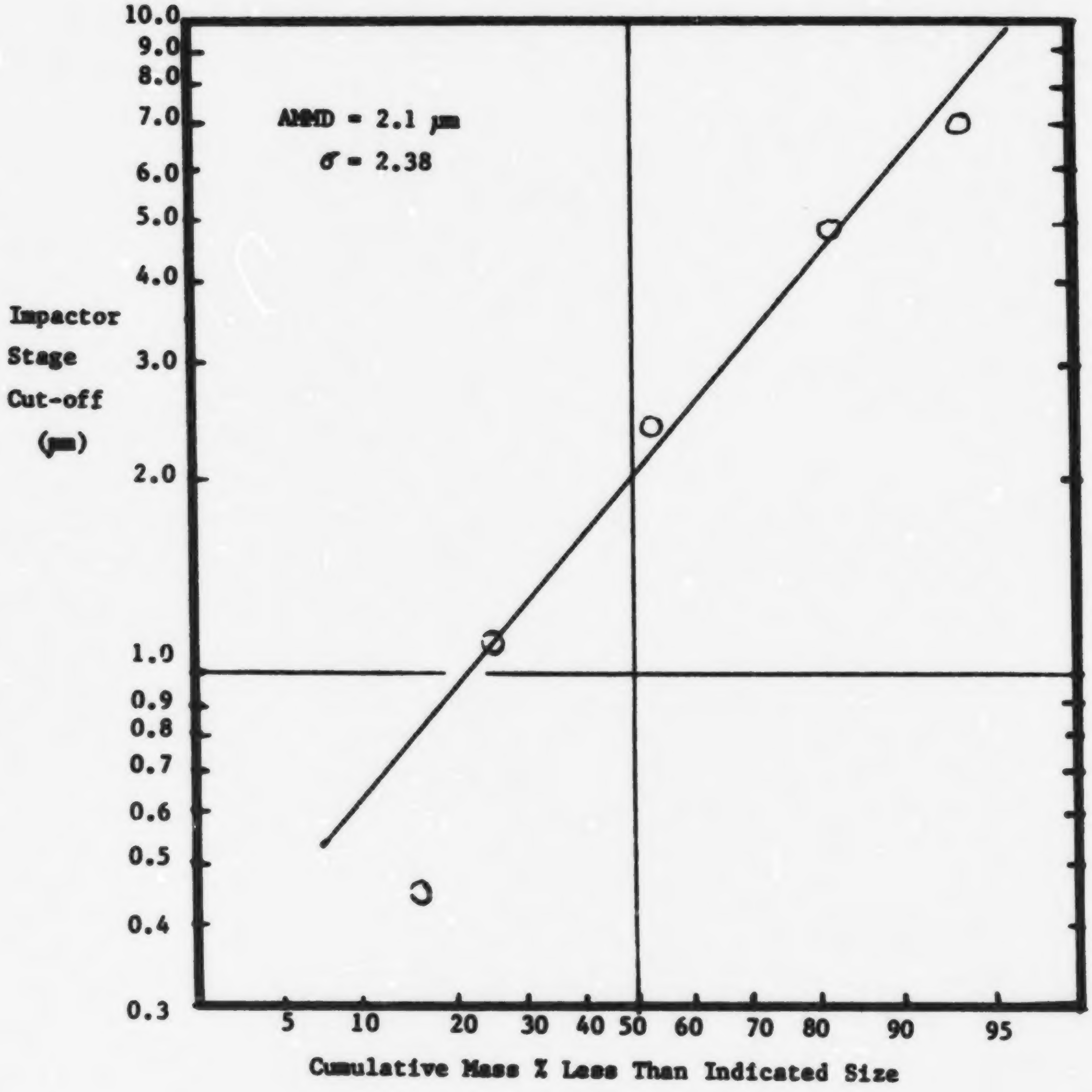

FIGURE 12: Cumulative mass % vs. Impactor stage cut-off for droplets from water sheet break-up in reversed configuration of spray nozzle.

622

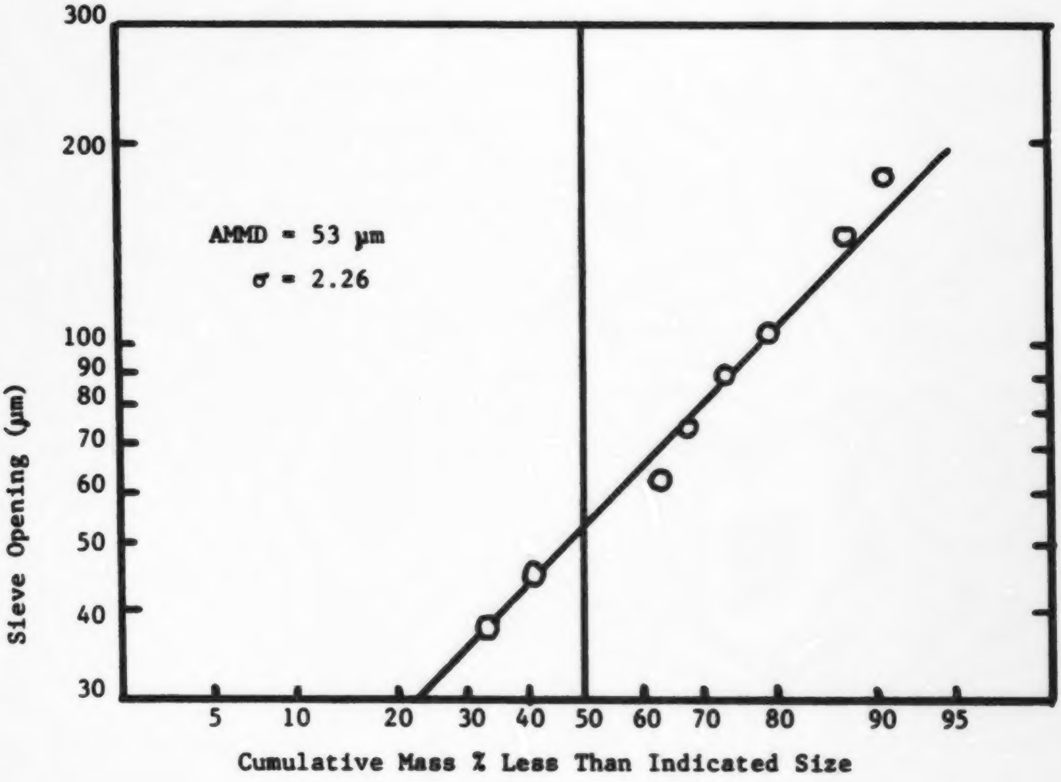

Figure 13: Cumulative Mass % Less Than Indicated Size vs. Sieve opening for frozen fallout droplets from water jet break-up in "normal" configuration of spray nozzle.

623

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Appendix B

MB-2 DATA CHANNEL/INSTRUMENTATION LIST

Engineering Test Facility
MB-2 Digital Data Acquisition System
Channel List
4/ 3/85   17:43:11

Channel	Instrument	Function				Range		Key	Offset	Slope	Last Mod
1	PTC-1	HOT	R12	C2	2.0	560.0 - 650.0	DEG F	1	179.288	23.09859	10/ 4/83
2	PTC-2	HOT	R 8	C2	2.0	500.0 - 650.0	DEG F	1	179.288	23.09859	11/ 8/84
3	PTC-3	HOT	R 5	C2	2.0	500.0 - 650.0	DEG F	1	179.288	23.09859	6/29/83
4	PTC-5	HOT	R12	C2	6.0	500.0 - 650.0	DEG F	1	179.288	23.09859	6/29/83
5	PTC-6	HOT	R 8	C2	6.0	500.0 - 650.0	DEG F	1	179.288	23.09859	6/29/83
6	PTC-7	HOT	R 5	C2	6.0	500.0 - 650.0	DEG F	1	179.288	23.09859	6/29/83
7	PTC-10	HOT	R 8	C3	10.0	500.0 - 650.0	DEG F	1	179.288	23.09859	6/29/83
8	PTC-11	HOT	R 5	C3	10.0	500.0 - 650.0	DEG F	1	179.288	23.09859	6/29/83
9	PTC-13	HOT	R 8	C2	15.5	500.0 - 650.0	DEG F	1	179.288	23.09859	6/29/83
10	PTC-14	HOT	R 5	C3	15.5	500.0 - 650.0	DEG F	1	179.288	23.09859	6/29/83
11	PTC-16	HOT	R 9	C2	21.0	500.0 - 650.0	DEG F	1	179.288	23.09859	6/29/83
12	PTC-17	HOT	R 4	C2	21.0	500.0 - 650.0	DEG F	1	179.288	23.09859	6/29/83
13	PTC-19	HOT	R 9	C3	26.0	500.0 - 650.0	DEG F	1	179.288	23.09859	6/29/83
14	PTC-20	HOT	R 4	C3	30.0	500.0 - 650.0	DEG F	1	179.288	23.09859	1/26/84
15	PTC-21	HOT	R 9	C3	34.0	500.0 - 650.0	DEG F	1	179.288	23.09859	6/29/83
16	PTC-22	HOT	R 4	C3	38.0	500.0 - 650.0	DEG F	1	179.288	23.09859	6/29/83
17	PTC-23	HOT	R10	C2	50.0	500.0 - 650.0	DEG F	1	179.288	23.09859	6/29/83
18	PTC-24	HOT	R 3	C2	50.0	500.0 - 650.0	DEG F	1	179.288	23.09859	6/29/83
19	PTC-25	HOT	R10	C3	90.0	500.0 - 650.0	DEG F	1	179.288	23.09859	6/29/83
20	PTC-26	HOT	R 3	C2	90.0	500.0 - 650.0	DEG F	1	179.288	23.09859	6/29/83
21	PTC-27	HOT	R10	C3	130.0	500.0 - 650.0	DEG F	1	179.288	23.09859	10/ 8/84
22	PTC-28	HOT	R 3	C2	130.0	500.0 - 650.C	DEG F	1	179.288	23.09859	6/29/83
23	PTC-30	HOT	R11	C3	170.0	500.0 - 650.0	DEG F	1	179.288	23.09859	6/29/83
24	PTC-31	HOT	R 3	C3	170.0	500.0 - 650.0	DEG F	1	179.288	23.09859	6/29/83
25	PTC-32	HOT	R11	C3	220.00	500.0 - 650.0	DEG F	1	179.288	23.09859	6/29/83
26	PTC-33	HOT	R 3	C3	220.00	500.0 - 650.0	DEG F	1	179.288	23.09859	6/29/83
27	PTC-34	COLD	R11	C2	2.0	500.0 - 650.0	DEG F	1	179.288	23.09859	6/29/83
28	PTC-35	COLD	R 9	C2	2.0	500.0 - 650.0	DEG F	1	179.288	23.09859	6/29/83
29	PTC-36	COLD	R 4	C2	2.0	500.0 - 650.0	DEG F	1	179.288	23.09859	6/29/83
30	PTC-38	COLD	R11	C2	6.0	500.0 - 650.0	DEG F	1	179.288	23.09859	6/29/83
31	PTC-39	COLD	R 9	C2	6.0	500.0 - 650.0	DEG F	1	179.288	23.09859	6/29/83
32	PTC-40	COLD	R 4	C2	6.0	500.0 - 650.0	DEG F	1	179.288	23.09859	1/17/84
33	PTC-42	COLD	R 7	C2	10.0	500.0 - 650.0	DEG F	1	179.288	23.09859	6/29/83
34	PTC-45	COLD	R 7	C2	21.0	500.0 - 650.0	DEG F	1	179.288	23.09859	6/29/83
35	PTC-47	COLD	R 8	C3	30.0	500.0 - 650.0	DEG F	1	179.288	23.09859	6/29/83
36	PTC-49	COLD	R 6	C2	50.0	500.0 - 650.0	DEG F	1	179.288	23.09859	6/29/83
37	PTC-50	COLD	R 6	C2	90.0	500.0 - 650.0	DEG F	1	179.288	23.09859	6/29/83
38	PTC-52	COLD	R 5	C2	170.0	500.0 - 650.0	DEG F	1	179.288	23.09859	6/27/83
39	PTC-53	COLD	R 8	C3	220.00	500.0 - 650.0	DEG F	1	179.288	23.09859	6/29/83
40	STC-1	HOT	R11.5	C2.5	1.0	450.0 - 550.0	DEG F	2	173.143	23.50395	6/29/83
41	STC-2	HOT	R 8.5	C2.5	1.0	450.0 - 550.0	DEG F	2	173.143	23.50395	6/29/83
42	STC-5	HOT	R11.5	C2.5	3.75	450.0 - 550.0	DEG F	2	173.143	23.50395	6/29/83
43	STC-6	HOT	R 8.5	C2.5	3.75	450.0 - 550.0	DEG F	2	173.143	23.50395	6/29/83
44	STC-7	HOT	R 4.5	C2.5	3.75	450.0 - 550.0	DEG F	2	173.143	23.50395	6/29/83
45	STC-10	HOT	R 8.5	C2.5	8.0	450.0 - 550.0	DEG F	2	173.143	23.50395	6/29/83
46	STC-11	HOT	R 4.5	C2.5	8.0	450.0 - 550.0	DEG F	2	173.143	23.50395	6/29/83
47	STC-13	HOT	R 8.5	C2.5	13.0	450.0 - 550.0	DEG F	2	173.143	23.50395	6/29/83
48	STC-14	HOT	R 4.5	C2.5	13.0	450.0 - 550.0	DEG F	2	173.143	23.50395	6/29/83
49	STC-17	HOT	R 8.5	C2.5	18.0	450.0 - 550.0	DEG F	2	173.143	23.50395	6/29/83
50	STC-18	HOT	R 4.5	C2.5	18.0	450.0 - 550.0	DEG F	2	173.143	23.50395	6/29/83
51	STC-19	HOT	R 8.5	C2.5	23.0	450.0 - 550.0	DEG F	2	173.143	23.50395	6/29/83

Engineering Test Facility
HB-2 Digital Data Acquisition System
Channel List
4/ 3/85 17:43:11

Channel	Instrument	Function	Range	Key	Offset	Slope	Last Mod
52	STC-20	HOT R 4.5 C2.5 23.0	450.0 - 550.0 DEG F	2	173.143	23.50395	6/29/83
53	STC-21	HOT R 8.5 C2.5 30.0	450.0 - 550.0 DEG F	2	173.143	23.50395	6/29/83
54	STC-22	HOT R 4.5 C2.5 34.0	450.0 - 550.0 DEG F	2	173.143	23.50395	6/29/83
55	STC-23	HOT R 8.5 C2.5 42.0	450.0 - 550.0 DEG F	2	173.143	23.50395	6/29/83
56	STC-26	HOT R 3.5 C2.5 70.0	450.0 - 550.0 DEG F	2	173.143	23.50395	6/29/83
57	STC-27	HOT R10.5 C2.5 110.0	450.0 - 550.0 DEG F	2	173.143	23.50395	6/29/83
58	STC-30	HOT R 2.5 C2.5 150.0	450.0 - 550.0 DEG F	2	173.143	23.50395	6/29/83
59	STC-31	HOT R 9.5 C2.5 195.0	450.0 - 550.0 DEG F	2	173.143	23.50395	6/29/83
60	STC-34	HOT R 2.5 C2.5 260.0	450.0 - 550.0 DEG F	2	173.143	23.50395	6/29/83
61	STC-35	COLD R11.5 C2.5 1.0	450.0 - 550.0 DEG F	2	173.143	23.50395	6/29/83
62	STC-36	COLD R 8.5 C2.5 1.0	450.0 - 550.0 DEG F	2	173.143	23.50395	6/29/83
63	STC-39	COLD R11.5 C2.5 3.75	450.0 - 550.0 DEG F	2	173.143	23.50395	6/29/83
64	STC-40	COLD R 8.5 C2.5 3.75	450.0 - 550.0 DEG F	2	173.143	23.50395	6/29/83
65	STC-41	COLD R 4.5 C2.5 3.75	450.0 - 550.0 DEG F	2	173.143	23.50395	6/29/83
66	STC-43	COLD R 8.5 C2.5 8.0	450.0 - 550.0 DEG F	2	173.143	23.50395	6/29/83
67	STC-44	COLD R 4.5 C2.5 8.0	450.0 - 550.0 DEG F	2	173.143	23.50395	6/29/83
68	STC-47	COLD R 6.5 C2.5 15.5	450.0 - 550.0 DEG F	2	173.143	23.50395	6/29/83
69	STC-49	COLD R 8.5 C2.5 23.0	450.0 - 550.0 DEG F	2	173.143	23.50395	6/29/83
70	STC-51	COLD R 8.5 C2.5 30.0	450.0 - 550.0 DEG F	2	173.143	23.50395	6/29/83
71	STC-53	COLD R 5.5 C2.5 70.0	450.0 - 550.0 DEG F	2	173.143	23.50395	6/29/83
72	STC-54	COLD R 5.5 C2.5 130.0	450.0 - 550.0 DEG F	2	173.143	23.50395	6/29/83
73	STC-55	COLD R 6.5 C2.5 195.0	450.0 - 550.0 DEG F	2	173.143	23.50395	6/29/83
74	TTC-1	HOT R11 C2 1.0	500.0 - 600.0 DEG F	3	177.434	23.21730	6/29/83
75	TTC-2	HOT R 9 C2 1.0	500.0 - 600.0 DEG F	3	177.434	23.21730	6/29/83
76	TTC-5	HOT R11 C2 3.75	500.0 - 600.0 DEG F	3	177.434	23.21730	6/29/83
77	(N.C.)						
78	TTC-7	HOT R 4 C2 3.75	500.0 - 600.0 DEG F	3	177.434	23.21730	6/29/83
79	TTC-10	HOT R 9 C2 8.0	500.0 - 600.0 DEG F	3	177.434	23.21730	6/29/83
80	TTC-11	HOT R 4 C2 8.0	500.0 - 600.0 DEG F	3	177.434	23.21730	6/29/83
81	TTC-13	HOT R 9 C2 13.0	500.0 - 600.0 DEG F	3	177.434	23.21730	6/29/83
82	TTC-14	HOT R 4 C2 13.0	500.0 - 600.0 DEG F	3	177.434	23.21730	6/29/83
83	JTC-17	HOT R 8 C2 18.0	500.0 - 600.0 DEG F	3	177.434	23.21730	6/29/83
84	TTC-18	HOT R 5 C2 18.0	500.0 - 600.0 DEG F	3	177.434	23.21730	6/29/83
85	TTC-19	HOT R 8 C2 23.0	500.0 - 600.0 DEG F	3	177.434	23.21730	6/29/83
86	(N.C.)						
87	TTC-21	HOT R 9 C2 30.0	500.0 - 600.0 DEG F	3	177.434	23.21730	6/29/83
88	TTC-22	HOT R 8 C2 42.0	500.0 - 600.0 DEG F	3	177.434	23.21730	6/29/83
89	TTC-23	HOT R10 C2 70.0	500.0 - 600.0 DEG F	3	177.434	23.21730	6/29/83
90	TTC-24	HOT R10 C2 110.0	500.0 - 600.0 DEG F	3	177.434	23.21730	6/29/83
91	TTC-25	HOT R10 C2 150.0	500.0 - 600.0 DEG F	3	177.434	23.21730	6/29/83
92	TTC-26	HOT R10 C2 195.0	500.0 - 600.0 DEG F	3	177.434	23.21730	6/29/83
93	TTC-27	HOT R10 C2 260.0	500.0 - 600.0 DEG F	3	177.434	23.21730	6/29/83
94	(N.C.)						
95	TTC-29	COLD R 8 C2 1.0	500.0 - 600.0 DEG F	3	177.434	23.21730	6/29/83
96	TTC-32	COLD R12 C2 3.75	500.0 - 600.0 DEG F	3	177.434	23.21730	6/29/83
97	TTC-33	COLD R 8 C2 3.75	500.0 - 600.0 DEG F	3	177.434	23.21730	6/29/83
98	TTC-34	COLD R 5 C2 3.75	500.0 - 600.0 DEG F	3	177.434	23.21730	6/29/83
99	TTC-36	COLD R 8 C2 8.0	500.0 - 600.0 DEG F	3	177.434	23.21730	6/29/83
100	TTC-37	COLD R 5 C2 8.0	500.0 - 600.0 DEG F	3	177.434	23.21730	6/29/83
101	TTC-40	COLD R 7 C2 15.5	500.0 - 600.0 DEG F	3	177.434	23.21730	6/29/83
102	TTC-42	COLD R 9 C2 23.0	500.0 - 600.0 DEG F	3	177.434	23.21730	6/29/83

Engineering Test Facility
HD-2 Digital Data Acquisition System
Channel List
4/ 3/85 17:43:11

Channel	Instrument	Function	Range		Key	Offset	Slope	Last Mod
103	TTC-44	COLD R 8 C2 30.0	300.0 - 600.0	DEG F	3	177.434	23.21730	6/29/83
104	TTC-45	COLD R 6 C2 70.0	300.0 - 600.0	DEG F	3	177.434	23.21730	6/29/83
105	TTC-46	COLD R 6 C2 130.0	300.0 - 600.0	DEG F	3	177.434	23.21730	6/29/83
106	TTC-47	COLD R 6 C2 195.0	300.0 - 600.0	DEG F	3	177.434	23.21730	6/29/83
107	DTC-2	HOT LEG DOWNCOMER 46.5	400.0 - 500.0	DEG F	2	173.143	23.30375	10/28/83
108	DTC-4	COLD LEG DOWNCOMER 46.5	400.0 - 500.0	DEG F	2	173.143	23.30375	10/28/83
109	DTC-5B	SHELL "DEAD SPACE" 31.25	400.0 - 500.0	DEG F	2	173.143	23.30375	6/29/83
110	DTC-6A	SHELL "DEAD SPACE" 231.0	400.0 - 500.0	DEG F	2	173.143	23.30375	6/29/83
111	DTC-7A	HOT LEG DOWNCOMER 325.0	400.0 - 500.0	DEG F	2	173.143	23.30375	10/28/83
112	DTC-8A	COLD LEG DOWNCOMER 325.0	400.0 - 500.0	DEG F	2	173.143	23.30375	10/28/83
113	DTC-9	HOT LEG DOWNCOMER 145.0	400.0 - 500.0	DEG F	2	173.143	23.30375	10/28/83
114	DTC-10	HOT LEG DOWNCOMER 240.0	400.0 - 500.0	DEG F	2	173.143	23.30375	10/28/83
115	DTC-11	BELOW FW INLET 300.0	400.0 - 500.0	DEG F	2	173.143	23.30375	6/29/83
116	DTC-12	ABOVE FW INLET 400.0	400.0 - 500.0	DEG F	2	173.143	23.30375	6/29/83
117	WTC-1	HOT LEG WRAPPER BOX 30.0	400.0 - 500.0	DEG F	2	173.143	23.30375	10/28/83
118	WTC-2	HOT LEG WRAPPER BX 231.0	400.0 - 500.0	DEG F	2	173.143	23.30375	10/28/83
119	WTC-3	COLD LEG WRAPPER BOX 30.0	400.0 - 500.0	DEG F	2.	173.143	23.30375	10/28/83
120	WTC-4	COLD LEG WRAPPER BX 231.0	400.0 - 500.0	DEG F	2	173.143	23.30375	10/28/83
121	(N.C.)							
122	T-602	TEST STAND TEMP (31' ELEVATION ON P-91)	40.0 - 120.0	DEG F	4	151.749	29.44692	10/ 8/84
123	T-603	TEST STAND TEMP (37' ELEVATION ON P-91)	40.0 - 120.0	DEG F	4	151.749	29.44692	10/ 8/84
124	T-279	AUXILIARY FEEDWATER OUTLET TEMP	80.0 - 160.0	DEG F	5	150.095	28.52293	10/ 3/83
125	DTC-7B	HOT LEG DOWNCOMER 325.0	400.0 - 500.0	DEG F	2	173.143	23.30375	6/ 1/84
126	DTC-8B	COLD LEG DOWNCOMER 325.0	400.0 - 500.0	DEG F	2	173.143	23.30375	6/ 1/84
127	DTC-10B	HOT LEG DOWNCOMER 240.0	400.0 - 500.0	DEG F	2	173.143	23.30375	6/ 1/84
128	T-601	TEST STAND TEMP (14' ELEVATION ON P-91)	40.0 - 120.0	DEG F	4	151.749	29.44692	10/ 8/84
129	STC-60	RISER 263.0	400.0 - 500.0	DEG F	2	173.143	23.30375	10/ 8/84
130	STC-61	SECONDARY SEPARATOR EXIT STEAM TEMP (E)	400.0 - 500.0	DEG F	2	173.143	23.30375	10/ 8/84
131	STC-62	SECONDARY SEPARATOR EXIT STEAM TEMP (W)	400.0 - 500.0	DEG F	2	173.143	23.30375	10/ 8/84
132	ETC-1	SDHV CONDENSER INLET TEMP	200.0 - 500.0	DEG F	6	158.153	24.00041	2/27/85
133	ETC-2	SDHV CONDENSER OUTLET TEMP	50.0 - 200.0	DEG F	16	50.000	.15000	2/27/85
134	ETC-3	SDHV CONDENSER INLET COOLING WATER TEMP	50.0 - 120.0	DEG F	8	151.521	29.34502	2/27/85
135	ETC-4	SDHV CONDENSER OUTLET COOLING WATER TEMP	50.0 - 200.0	DEG F	7	149.412	28.41072	2/27/85
136	ETC-5	SDHV COOLING WATER TEMP	50.0 - 120.0	DEG F	8	151.521	29.34502	2/27/85
137	ETC-6	SDHV COLLECTION TANK TEMP	50.0 - 200.0	DEG F	7	149.412	28.41072	2/27/85
138	T-604	TEST STAND TEMP (EIGHTH DECK)	40.0 - 120.0	DEG F	4	151.749	29.44692	10/11/84
139	RM-1	CONDENSATE RESISTIVITY	.0 - 20.0	MOHM/CM	12	-5.000	.02500	3/18/85
140	CM-1	B-1 CONDUCTIVITY	.0 - 2000.0	uSIEM/CM	15	-500.000	2.50000	3/18/85
141	CM-2	IRP-4 CONDUCTIVITY	.0 - 2000.0	uSIEM/CM	15	-500.000	2.50000	3/18/85
142	CM-3	PRIMARY CONDUCTIVITY	.0 - 2000.0	uSIEM/CM	15	-500.000	2.50000	3/18/85
143	(N.C.)							
144	(N.C.)							
145	(N.C.)							
146	(N.C.)							
147	(N.C.)							
148	(N.C.)							
149	(N.C.)							
150	(N.C.)							
151	(N.C.)							
152	(N.C.)							
153	(N.C.)							

626

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Engineering Test Facility
MD-2 Digital Data Acquisition System
Channel List
4/ 3/85 17:43:11

Channel	Instrument	Function	Range	Key	Offset	Slope	Last Mod
154	(N.C.)						
155	(N.C.)						
156	(N.C.)						
157	(N.C.)						
158	(N.C.)						
159	(N.C.)						
160	(N.C.)						
161	(N.C.)						
162	(N.C.)						
163	(N.C.)						
164	(N.C.)						
165	(N.C.)						
166	(N.C.)						
167	(N.C.)						
168	(N.C.)						
169	(N.C.)						
170	(N.C.)						
171	(N.C.)						
172	(N.C.)						
173	(N.C.)						
174	(N.C.)						
175	(N.C.)						
176	(N.C.)						
177	(N.C.)						
178	(N.C.)						
179	(N.C.)						
180	(N.C.)						
181	(N.C.)						
182	(N.C.)						
183	(N.C.)						
184	(N.C.)						
185	(N.C.)						
186	(N.C.)						
187	(N.C.)						
188	(N.C.)						
189	(N.C.)						
190	(N.C.)						
191	(N.C.)						
192	CLOCK	MANUALLY INITIATED TIME MARK	.0 - 16.0 NOT CONN	20	.000	.00000	7/16/84
193	DPT-0007	SEC SEPARATOR DRAIN PIPE WATER LEVEL	.0 - 92.0 INCH WC	193	-23.000	.02875	10/ 8/84
194	T-1151	S/G PRIMARY THOT (LOWER RANGE)	200.0 - 500.0 DEG F	194	200.000	.07500	3/ 1/85
195	T-1150	S/G PRIMARY THOT (UPPER RANGE)	500.0 - 650.0 DEG F	195	500.000	.03750	3/ 1/85
196	T-1250	S/G PRIMARY TCOLD	250.0 - 650.0 DEG F	196	250.000	.10000	3/ 1/85
197	DP-0404A	TUBE BUNDLE VOID FRACTION	.0 - 100.0 INCH WC	197	-25.000	.03125	12/18/84
198	DP-0808A	TUBE BUNDLE VOID FRACTION	-20.0 - 52.0 INCH WC	198	-38.000	.02250	10/ 8/84
199	DPT-1090	S/G PRIMARY FLOW (WIDE RANGE - ANNUBAR)	.0 - 191.0 INCH WC	199	.000	.04775	1/17/84
200	DPT-1091	S/G PRIMARY FLOW (MIDDLE RANGE -ANNUBAR)	.0 - 20.0 INCH WC	200	-5.000	.00625	1/17/84
201	DPT-2990	AUXILIARY FEEDWATER FLOW (WIDE RANGE)	.0 - 2425.0 INCH WC	201	.000	.60625	3/28/85
202	DPT-111	PRIMARY LOW FLOW (VENTURI)	.0 - 268.0 INCH WC	202	.000	.06700	1/17/84
203	P-139	PRESSURIZER PRESS (UPPER RANGE)	900.0 - 2500.0 PSIG	203	900.000	.40000	3/ 1/85
204	P-140	PRESSURIZER PRESS (LOWER RANGE)	.0 - 1250.0 PSIG	204	-312.500	.39063	3/ 1/85

627

Engineering Test Facility
MB-2 Digital Data Acquisition System
Channel List
4/ 3/85 17:43:11

Channel	Instrument	Function	Range		Key	Offset	Slope	Last Mod
205	LT-9414	S/G VOID WATER LEVEL (WIDE RANGE)	.0 - 510.0	INCHES	205	-127.500	.15938	11/ 9/84
206	DPT-2016	FEEDWATER FLOW (MIDDLE RANGE)	.0 - 20.0	INCH WC	206	-5.000	.00625	10/ 3/83
207	DPT-110	PRIMARY LOOP FLOW	.0 - 500.0	INCH WC	207	.000	.12500	9/29/83
208	F-109	S/G PRIMARY FLOW (WIDE RANGE - ANNUBAR)	.0 - 120.0	PERCENT	208	.000	.03000	1/17/84
209	T-265	FEEDWATER HEATER OUTLET TEMP	50.0 - 500.0	DEG F	209	50.000	.11250	3/27/81
210	T-2101	S/G INLET FEEDWATER TEMP	50.0 - 500.0	DEG F	210	50.000	.11250	3/27/81
211	T-2201	S/G EXIT STEAM TEMP	300.0 - 450.0	DEG F	211	300.000	.03750	3/27/81
212	P-13	S/G PRIMARY PRESS (TCOLD)	.0 - 3000.0	PSIG	212	.000	.75000	7/16/84
213	P-2101	S/G INLET FEEDWATER PRESS	750.0 - 1500.0	PSIG	213	750.000	.18750	3/27/81
214	PT-91	S/G EXIT PRESS	.0 - 1500.0	PSIG	214	.000	.37500	2/27/85
215	P-255	STEAM HEADER PRESS	.0 - 1500.0	PSIG	215	.000	.37500	10/28/83
216	P-299	AUXILIARY FEEDWATER PRESS	1100.0 - 1600.0	PSIG	216	975.000	.15625	1/17/84
217	P-42	FEEDWATER HEATER INLET STEAM PRESS	.0 - 1500.0	PSIG	217	.000	.37500	3/27/81
218	DPT-2998	AUXILIARY FEEDWATER FLOW (NARROW RANGE)	.0 - 690.0	INCH WC	218	-172.500	.21563	3/29/85
219	DPT-9304	WRAPPER BOX DIFFERENTIAL PRESSURE	-150.0 - 150.0	PSID	219	-150.000	.07500	12/11/84
220	P-261	FEEDWATER HEATER OUTLET FEEDWATER PRESS	.0 - 1500.0	PSIG	220	.000	.37500	3/27/81
221	L-9321	S/G WATER LEVEL (WIDE RANGE)	14.5 - 500.0	INCHES	221	14.500	.12138	11/ 8/84
222	L-9360	S/G WATER LEVEL (NARROW RANGE)	303.1 - 500.0	INCHES	222	303.100	.03125	1/17/84
223	T-290	FEEDWATER PUMP DISCHARGE TEMP	25.0 - 350.0	DEG F	223	25.000	.08125	7/16/84
224	F-220	STEAM FLOW (WIDE RANGE - ORIFICE)	.0 - 175.0	PERCENT	224	.000	.04375	1/17/84
225	DPT-1901	HL DOWNCOMER DUCT & WRAPPER OPENING LOSS	-60.0 - 60.0	INCH WC	225	-90.000	.03750	12/18/84
226	DPT-9360	S/G WATER LEVEL DP (NARROW RANGE)	.0 - 152.0	INCH WC	226	-38.000	.04750	10/ 8/84
227	DPT-0904	TUBE SUPPORT PLATE 04 LOSS	-88.0 - .0	INCH WC	227	-110.000	.02750	10/ 8/84
228	PT-2	SGRV CONDENSER OUTLET PRESS	.0 - 750.0	INCH WC	228	-187.500	.23438	3/22/85
229	DPT-6160	PRIMARY SEPARATOR RISER	.0 - 44.0	INCH WC	229	-11.000	.01375	9/29/83
230	DPT-0208	SEC SEPARATOR DRAIN PIPE WATER LEVEL	.0 - 140.0	INCH WC	230	-35.000	.04375	10/ 8/84
231	DPT-6269	PRIMARY SEPARATOR ORIFICE LOSS	-36.0 - 60.0	INCH WC	231	-60.000	.03000	10/ 8/84
232	DPT-0069	STEAM SHROUD & SEC SEPARATOR INLET LOSS	.0 - 40.0	INCH WC	232	-10.000	.01250	9/29/83
233	DPT-0201	SEC SEPARATOR OUTLET LOSS	-28.0 - 32.0	INCH WC	233	-43.000	.01875	10/ 8/84
234	DPT-2	SGRV COOLING WATER FLOW	.0 - 350.0	INCH WC	234	-87.500	.10938	2/27/85
235	DPT-4100	STEAM FLOW (NARROW RANGE - ANNUBAR)	.0 - 8.0	INCH WC	235	-2.000	.00250	1/17/84
236	DPT-9223	HL DOWNCOMER DUCT WATER LEVEL (TOP)	-80.0 - 100.0	INCH WC	236	-125.000	.05625	12/13/84
237	PT-3	SGRV COOLING WATER PRESS	.0 - 150.0	PSIG	237	-37.500	.04688	2/27/85
238	DPT-0760	BUNDLE PLENUM TO RISER TRANSITION LOSS	-120.0 - .0	INCH WC	238	-150.000	.03750	10/ 8/84
239	DPT-0001	SECONDARY SEPARATOR LOSS	-4.0 - 16.0	INCH WC	239	-9.000	.00625	12/18/84
240	DPT-0405	TUBE SUPPORT PLATE 05 LOSS	-60.0 - .0	INCH WC	240	-75.000	.01875	10/ 8/84
241	DPT-6072	DOWNCOMER FUNNEL LOSS (HOT LEG)	.0 - 240.0	INCH WC	241	-60.000	.07500	12/ 5/84
242	DPT-0791	TUBE BUNDLE TO STEAM EXIT LOSS	-50.0 - 950.0	PSID	242	-300.000	.31250	2/27/85
243	DPT-130	BREAK INJECTION FLOW (VENTURI)	.0 - 750.0	INCH WC	243	-187.500	.23438	7/30/84
244	DPT-0009	TUBE SUPPORT GRID 03 LOSS	-30.0 - 30.0	INCH WC	244	-45.000	.01875	10/ 8/84
245	DPT-1	SGRV CONDENSATE FLOW	.0 - 150.0	INCH WC	245	-37.500	.04688	2/27/85
246	DPT-0102	FLOW DISTRIBUTION BAFFLE LOSS	-25.0 - 35.0	INCH WC	246	-40.000	.01875	10/ 8/84
247	DPT-0203	TUBE SUPPORT PLATE 01 LOSS	-70.0 - 18.0	INCH WC	247	-92.000	.02750	10/ 8/84
248	DPT-9193	S/G WATER LEVEL FOR OVERFILL INDICATION	-20.0 - 60.0	INCH WC	248	-40.000	.02500	3/ 1/85
249	DPT-0607	U-BEND REGION LOSS	-60.0 - 8.0	INCH WC	249	-77.000	.02125	10/ 8/84
250	DPT-2998	AUXILIARY FEEDWATER FLOW (PHASE II)	.0 - 750.0	INCH WC	250	-187.500	.23438	3/15/85
251	DPT-6069	UPPER DOWNCOMER LOSS	-132.0 - .0	INCH WC	251	-165.000	.04125	10/ 8/84
252	DPT-9219	HL DOWNCOMER DUCT WATER LEVEL (MIDDLE)	-120.0 - 300.0	INCH WC	252	-225.000	.13125	12/18/84
253	DPT-1942	HL DOWNCOMER DUCT WATER LEVEL (BOTTOM)	-4.0 - 48.0	INCH WC	253	-17.000	.01625	10/ 8/84
254	DPT-2001	CL DOWNCOMER DUCT & WRAPPER OPENING LOSS	-40.0 - 100.0	INCH WC	254	-75.000	.04375	12/18/84
255	DPT-0506	TUBE SUPPORT PLATE 06 LOSS	-30.0 - 30.0	INCH WC	255	-45.000	.01875	10/ 8/84

628

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MB-2 Digital Data Acquisition System
Channel List
4/ 3/85 17:43:11

Channel	Instrument	Function	Range	Key	Offset	Slope	Last Mod
256	DPT-0107	TUBE BUNDLE LOSS	-200.0 - .0 INCH WC	256	-350.000	.00750	9/29/83
257	DPT-3031	HL DOWNCOMER DUCT PITOT STATIC PROBE 01	.0 - 16.0 INCH WC	257	-4.000	.00500	12/18/84
258	DPT-3233	CL DOWNCOMER DUCT PITOT STATIC PROBE 01	.0 - 16.0 INCH WC	258	-4.000	.00500	12/18/84
259	DPT-0965	DECK PLATE LOSS	-60.0 - 36.0 INCH WC	259	-64.000	.03000	11/ 8/84
260	DPT-0300	TUBE SUPPORT PLATE 02 LOSS	-102.0 - 10.0 INCH WC	260	-130.000	.03500	11/ 8/84
261	DPT-6165	PRIMARY SEPARATOR TOTAL LOSS	-60.0 - 220.0 INCH WC	261	-130.000	.00750	11/ 8/84
262	DPT-1112	S/G PRIMARY TUBE BUNDLE LOSS	.0 - 800.0 INCH WC	262	-200.000	.25000	9/29/83
263	DPT-9321	S/G WATER LEVEL DP (WIDE RANGE)	.0 - 520.0 INCH WC	263	-130.000	.16250	11/21/84
264	DPT-9914	S/G SHELL VOID WATER LEVEL DP	.0 - 40.0 INCH WC	264	-12.000	.01500	6/19/84
265	P-211	FE-220 INLET PRESS	450.0 - 1200.0 PSIG	265	450.000	.18750	9/29/83
266	P-7	S/G SECONDARY BUNDLE PRESSURE	.0 - 1500.0 PSIG	266	.000	.37500	9/29/83
267	DPT-2010	FEEDWATER FLOW (WIDE RANGE)	.0 - 203.0 INCH WC	267	.000	.05075	9/29/83
268	DPT-2200	STEAM FLOW (WIDE RANGE - ORIFICE)	.0 - 600.0 INCH WC	268	.000	.15000	1/17/84
269	(N.C.)						
270	PT-1	SDRV CONDENSER INLET PRESS	.0 - 600.0 PSIG	270	.000	.15000	2/27/85
271	T-119	HEATER NO. 4 OUTLET TEMP	500.0 - 650.0 DEG F	271	500.000	.03750	10/20/81
272	LT-3	SDRV COLLECTION TANK LEVEL	.0 - 96.0 INCH WC	272	.000	.02400	2/27/85

Appendix C

DATA TAPES

Run. No.	Tape I.D.	Comments
T1952 - T1955	A03155	Test 2.3 and Tests 2.1/2.2 Shakedown
T1956 - T1957	A03185	Isothermal and 8% SORV Moisture
T1958 - T1967	A03205	8% SORV Shakedown, SORV Condensate Venturi Cal., Zero Diff. Cal. Check, Isothermal, and 100% Power Moisture Carryover Shakedown
T1968 - T1969	A03255	Isothermal and Zero Diff. Cal. Check
T1970	B03265	Test 2.2
T1971 - T1972	B03275	Test 2.1 and Zero Diff. Cal. Check
T1973 - T1979	A04015	Isothermal, Zero Diff. Cal. Check, and Test 2.4 (Revised)
T1980 - T1984	B04035	Isothermal, Zero Diff. Cal. Check, and Test 2.2 (Revised)
T1985 - T1994	A04095	Isothermal, Zero Diff. Cal. Check, and Test 2.3 (Revised)
T1996 - T1998	A04125	Isothermal, Zero Diff. Cal. Check, and Test 2.8 (Revised)

630

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DATA TAPES

Run. No.	Tape I.D.	Comments
T1999 - T2003	A04155	Zero Diff. Cal. Check, Test 2.9 (Revised), and Test 2.8 (Revised)
T2004	A04185	Isothermal
T2038 - T2047	A05145	Aerosol Testing, Test 2.6, Trials 1-10
T2048 - T2054	A05215	Isothermal, Zero Diff. Cal. Check, and Test 2.4 (Revised - Dryerless)
T2055 - T2057	C05215	MB-2 Mass Calibration
T2058 - T2059	A05225	MB-2 Mass Calibration
T2060 - T2062	A05235	Zero Diff. Cal. Check and Test 2.3 (Revised - Dryerless)
T2063 - T2065	B05235	Test 2.3 (Revised - Dryerless)
T2066 - T2068	A05245	Isothermal, Zero Diff. Cal. Check, and Test 2.2 (Revised-#2 - Dryerless)
T2069	C05245	100% Power Moisture Carryover - Dryerless

631

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Appendix D

MB-2 THERMAL-HYDRAULIC DATA REDUCTION

Test measurements obtained via the Data Acquisition System were first stored on disc and magnetic tape at the Engineering Test Facility. The information was then transmitted to the Westinghouse Monroeville Nuclear Center for reduction and analysis. The reduction of the raw data into the proper engineering units and the modification of the data to account for the necessary corrections, e.g., cold leg pressure drop corrections will be discussed in this appendix.

The first step in the data reduction operation was to process the raw data with the DEPAKIT computer program. Basically, this program performed a conversion of the raw measurements to the corresponding engineering units -- This process made use of predetermined calibration curves which related the measured quantity (e.g., voltage from a differential pressure cell) to the engineering parameter (e.g., its differential pressure in inches of water or psi). Use was made of the slopes and intercepts derived during the calibration of each instrument.

The next step in the data reduction operation was completed using the "MB-2" data reduction computer program. It accessed the measurements referred to in the preceding paragraph, made a number of necessary modifications to those values, and prepared tabulations and plots of the various measurements. The program was also used for the reduction of pretest instrument calibration data. A summary of the calculations performed by the "MB-2" program included:

1. Cold Leg Corrections -- Cold leg elevation head corrections were included for all differential pressure and absolute pressure measurements. The correction accounted for that portion of the pressure tube which was located within the MB-2 shell at an elevated temperature, and that portion which ran from the shell to the D/P transmitter and was exposed to ambient

632

conditions. Figure D-1 defines the general procedure used to correct the measured differential pressures for these cold leg effects. Table D-1 provides the locations of the pressure taps and the elevations at which the pressure lines exit the shell. Densities used in these calculations were based on conditions defined by the closest available temperature/pressure measurements.

The transmitter used for system pressure measurements were located below the tap elevations. The distances between the pressure taps and pressure transmitters used in elevation head corrections are given in Table D-2.

2. Flow Rate Calculations -- A number of differential pressure measurements were obtained for usa in determining flow rates. They include:

   primary flow
   feedwater flow (main and auxiliary)
   steam flow
   downcomer flows - hot and cold legs

   Flow rates were calculated from the general expression:

   $$W = K' * Ao * \sqrt{2g_c * \rho * \Delta P}$$

   where

   W = flow rate (lbm/hr)
   K' = flow coefficient
   Ao = flow element throat area (ft^2)
   g_c = gravitational constant
   ρ = density of fluid through flow element (lbm/ft^3)
   Δp = differential pressure of flowing fluid across flow element taps (lbf/ft^2)

633

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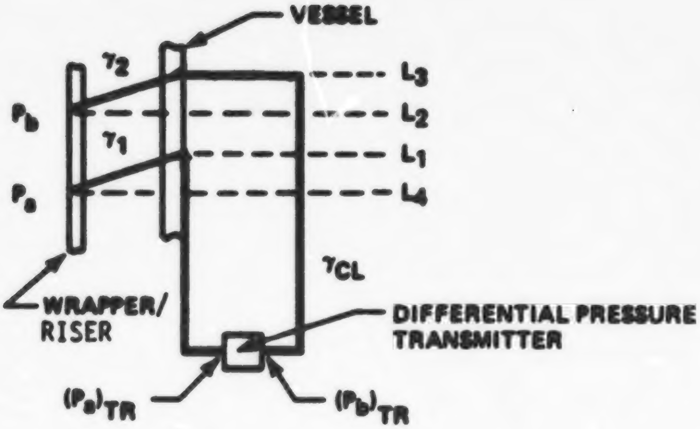
In this calculation the measured pressure drop was corrected for both hot and cold leg elevation head effects (where required) so that the resulting differential pressure included only the drop associated with the flowing fluid. Flow coefficients used in the calculations were derived from previous calibration test runs.


VESSEL
γ_2
L_3
P_b
L_2
γ_1
L_1
P_a
L_4
γ_{CL}
WRAPPER/
RISER
DIFFERENTIAL PRESSURE
TRANSMITTER
$(P_a)_{TR}$
$(P_b)_{TR}$

General Equation

$$P_a - P_b = (P_a - P_b)_{TR} + (L_1 - L_4)\gamma_1 - (L_3 - L_2)\gamma_2 + (L_3 - L_1)\gamma_{CL}$$

where:

P_a, P_b = Pressures at tap locations a and b, lb_f/ft^2

$(P_a)_{TR}$; $(P_b)_{TR}$ = Pressures at pressure transmitter, lb_f/ft^2

L_1, L_2, etc. = Elevations relative to a datum, ft

γ = Specific weight, lb_f/ft^3

Assumptions:
$\gamma_1 = \gamma_f$ if $L_4 > L_1$
$\gamma_2 = \gamma_f$ if $L_2 > L_3$
$\gamma_1 = \gamma_g$ if $L_1 > L_4$
$\gamma_2 = \gamma_g$ if $L_3 > L_2$

Subcripts f and g refer to saturated liquid and vapor at secondary side pressure conditions.

Figure D-1. Calculation of Differential Pressures

TABLE D-1

PRESSURE TAP ELEVATIONS FOR DIFFERENTIAL PRESSURE MEASUREMENT

Tap	Tap Location	Tap Elevation (in.)[1]	Shell Penetration Elevation (in.)*
P-42	Hot Leg Downcomer Duct	1.00	-4.25
P-01	Wrapper Box	17.00	17.00
P-21	Hot Leg Downcomer Duct	14.50	14.50
P-02	Wrapper Box	26.36	26.36
P-19	Hot Leg Downcomer Pipe	40.82	40.00
P-20	Cold Leg Downcomer Pipe	40.82	40.82
P-03	Wrapper Box	51.82	51.82
P-04	Wrapper Box	194.19	194.19
P-04A	Wrapper Box	164.00	81.82
P-05	Wrapper Box	235.96	235.96
P-06	Wrapper Box	250.96	250.96
P-07	Wrapper Box	286.59	286.59
P-08	Wrapper Box	111,82	111.82
P-08A	Wrapper Box	84.00	81.82
P-09	Wrapper Box	126.82	126.82
P-23	Hot Leg Downcomer Pipe	250.00	111.82
P-92	Hot Leg Downcomer Pipe	334.00	111.82
P-30	Hot Leg Downcomer Pitot	100.32	96.82
P-31	Hot Leg Downcomer Pitot	99.32	96.82
P-32	Cold Leg Downcomer Pitot	100.32	96.82
P-33	Cold Leg Downcomer Pitot	99.32	96.82
P-99	Lower Shell Dead Space	38.82	38.82
P-14	Lower Shell Dead Space	-4.25	-4.25

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(1) From top of tubesheet

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TABLE D-1 (Continued)

PRESSURE TAP ELEVATIONS FOR DIFFERENTIAL PRESSURE MEASUREMENT

Tap	Tap Location	Tap Elevation (in.)(1)	Shell Penetration Elevation (in.)*
P-60	Riser Pipe	383.2	382.1
P-61	Riser Pipe	423.0	422.0
P-62	Riser Pipe	474.3	476.8
P-65	Unit Cell	474.3	476.8
P-68	Downcomer Drum	383.1	382.1
P-69	Dryer Shroud	482.0	495.0
P-80	Secondary Separator	527.9	529.3
P-81	Secondary Separator	527.9	529.3
P-82	Dryer Drain	517.3	517.3
P-87	Dryer Drain	404.0	400.0
P-88	Dryer Drain	481.0	481.0
P-91	Shell Steam Line	561.8	---
P-93	Dryer Shroud	508.0	510.0
P-94	Shell	---	510.0

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(1) From top of tubesheet

637

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TABLE D-2

COLD LEG LENGTHS FOR SYSTEM PRESSURE TRANSMITTERS

Transmitter	Tap Location	Cold Leg Length (in.)*
P-7	Bundle	337
P-13	Primary Outlet	61
P-81	Steam Dome	527.9
P-91	Steam Line	582
P-139, P-140	Pressurizer	182.8
P-211	Steam Line	26.3
P-255	Steam Line	17
P-261	Feed Line	109
P-299	Auxiliary Feed Line	45
P-2101	Feed Line	43.8

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* Pressure tap elevation minus transmitter elevation

638

NRC FORM 335
(2-84)
NRCM 1102,
3201, 3202

U.S. NUCLEAR REGULATORY COMMISSION

BIBLIOGRAPHIC DATA SHEET

SEE INSTRUCTIONS ON THE REVERSE

1 REPORT NUMBER *(Assigned by TIDC, add Vol No., if any)*
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EPRI NP-4787
TPRD/L/3009/R86
WCAP-11226

2 TITLE AND SUBTITLE
Coincident Steam Generator Tube Rupture and Stuck-Open
Safety Relief Valve Carryover Tests
MB-2 Steam Generator Transient Response Test Program

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5 AUTHOR(S)
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R. Garnsey & M. Y. Young

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Nuclear Technology Systems Division
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Technology Planning and Research Division
Central Electricity Research Laboratorie
Kelvin Avenue
Leatherhead, Surry, KT22 7SE, U.K.

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Technical

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13 ABSTRACT *(200 words or less)*

In PWR steam generator tube rupture (SGTR) faults, a direct pathway for the release of radioactive fission products can exist if there is a coincident stuck-open safety relief valve (SORV) or if the safety relief valve is cycled. The test program consisted of sixteen separate tests designed to cover a range of steady-state and transient fault conditions.

The main conclusions from these tests were that moisture carryover was very low in the absence of an SGTR, that there was no significant increase in moisture carryover during an SGTR/SORV fault and that very little or no primary coolant passed through the steam generator without having first completely mixed with the bulk secondary liquid (primary coolant bypassing). Short-term perturbations to steady-state conditions were found to produce transient releases, which could be mainly due to primary coolant bypassing or these releases were the equivalent of steady-state releases over tens of hours, and could be important factors in determining the overall activity release in these types of fault. At very low water levels, when recirculation within the boiler could not be maintained, conditions typical of early stages in an SGTR/SORV fault produced large transient releases.

14 DOCUMENT ANALYSIS - a KEYWORDS/DESCRIPTORS
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b IDENTIFIERS/OPEN-ENDED TERMS

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639

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